Introduction
This is the first chapter of a book for seniors starting their senior project. This chapter gives an overview of TI, how seniors can use TI to their benefit, some useful URLs, and the basic rules of the Engibous Prize.

The senior project is an important experience for engineering students preparing for a career. The reason for its importance is that virtually all product development today is done by teams. These teams will have amazingly diverse personalities and training backgrounds. You will find that project teams can have as few as five or 10 people to hundreds of people. On these teams will be engineers with different training from different universities; they will not all specialize in the same thing. There will also be a large assortment of nontechnical people who are experts in areas that up until now may have been of little interest to you, such as marketing, program management, sales and market communications. As you grow in your career, you'll find each of these roles valuable to the success of a product.

Some of the best advice I received as a brand-new engineer out of college was from a senior government employee to whom I reported. I was in the army, serving two years as a draftee. After about a year under his command, he asked me into his office. The topic of our meeting was mentoring, and he asked if I had thought of becoming a manager. My response was a firm "no," as I enjoyed being an engineer and turning ideas into reality. His reply was interesting. He said, "Gene, some day you'll have an idea that will take more than two hands to develop. At that point, you will become a manager."

At this point, you may be trying to tie this story into useful information. Let me attempt to do that.

The purpose of a senior project is to gain experience working on a team. Fortunately, it will be with several other students whom you have known for three or four years and are comfortable working with. Or whom you **think** you are comfortable working with. If your team is like many teams you will encounter in an industrial setting, it will probably have one or two hard-driving individuals. It will also have one or two "lazy, not in a hurry, a C is good enough" individuals. It is with this team that you will have to

complete your senior project. As with any team, you will also need a leader; one of your members will become that leader, either by election or by default. The success of your project will depend heavily on the choice of leader.

As the team begins to function, an important question will come to your mind: How do I get graded on this project? Over the years, I have asked professors how they determine the grade for each individual and received responses like, “we watch them closely” and “we ask the team members to rate each other.” I see neither as satisfactory answers. Simply put, teams should be graded as teams and not as individuals.

The purpose of a team is to become greater than the sum of its individuals. This effect has happened on several teams to which I've belonged. As we teamed up, two began to look like five and five began to look like 10 and 10 began to look like 30. I call it “jelling.” Somehow we became significantly more productive as a team than as a group of individuals. The team was never made up of all hard-driving, passionate individuals; this effect is possible even with a random mix of people.

If you are still reading, you are probably waiting for me to provide the secret as to how this can happen on your team. Unfortunately, I don’t know. For just as the team “jelled,” it fell apart – rather mysteriously in both cases. But while we were jelling, we did have a few common traits:

- A leader emerged whom everyone was willing to follow. Notice I said leader and not manager. There is a difference between the two.
- A cheerleader emerged – someone who was around to encourage, excite and give credit to the individuals on the team and the team itself.
- No one was left sitting. Everyone was engaged and working toward the goal.
- We all liked each other.

Let me tie this all together. TI wants to be part of your team, but we don’t want to be the leader, cheerleader or lazy member. We want to do whatever we can to make your senior project experience one that you can be proud of, where you will remember TI as an extended member that made the

whole project fun. We want you to be ready to have TI as an extended member on your next project – the first one at whichever company you join after graduation.

This leads me to explain how can you get the most out of TI as an extended team member.

Purpose of this book

Use this book as a reference to pick the best TI parts for your project. As you will see later, TI has more than 40,000 components that you could use in your project. Narrowing that number down to one or two (or nine or 10) parts will be daunting. We hope to simplify that task by giving you some hints and shortcuts in this collection of topics to help you get what you need.

How to interact with Texas Instruments

Before we get to the quick overviews of each of our component families, let me introduce you to TI. Although we are generally known as the "calculator company," and that division is a small part of TI, our major business is integrated circuits. As I said earlier, we have more than 40,000 components in our catalog. That is where we can become a valuable member of your team.

There are many ways to get TI to join your project team:

- Use our components.
- Use our many application reports and white papers.
- Use our technical support.
- Use our evaluation modules (EVMs) to prototype.

But before I tell you about all of the resources we have available to you, let me give you the URL for the university program at Texas Instruments: http://www.ti.com/lsds/ti/university_program/ti_university_program.page.

This is a great place to start if you're just getting to know us. Now here are some resources that will help you with your senior project.

Use our components.http://www.ti.com/ is the best place to start your interaction with us. From this URL, you can find all you need to know about every product TI makes available. You can even get free samples shipped to you (if you don't already have them in your senior projects lab). We have just about everything you will need for your project. And if we don't have it, our partner Digi-Key will certainly have it (http://www.digikey.com/).

Use our many application reports and white papers. At http://www.ti.com/, you will find a tab for Applications. Here you will find a gold mine of application material. From the Applications page, look for your area of interest, and from there click the Application Notes tab.

Use our technical support. We have several ways for you to get technical support. Here are a few:

- Technical support line: You can find local support no matter where you are in the world or what language you are most comfortable using at http://www-k.ext.ti.com/sc/technical-support/product-information-centers.htm?DCMP=TIHomeTracking&HQS=Other+OT+home_d_contact.

- E2E Community: This not only connects you to TI's top applications engineers, but to others like you who have used our parts and may have already solved the same problem you are facing. Give it a try at http://e2e.ti.com/.

Videos that might be helpful:

- www.ti.com/universityvideos.
- TI's YouTube channel.

Use our evaluation modules to prototype. We have EVMs for virtually all of our embeddeed processors. They also include the analog and other interface circuits that work best with the processors. You will find TI EVMs by clicking Tools and Software at http://www.ti.com/.

In fact, you can find many sources of available software by clicking Tools and Software at http://www.ti.com/.

Engibous Prize entry requirements

One way that we recognize the effort that you and your team have put into your senior project is with the Engibous Prize. It is named after Tom Engibous, our now-retired president and CEO. Engibous spent his career at TI, starting as a design engineer in our analog circuit business unit. He was promoted from there to a management role, finally becoming president and CEO in the late 1990s until his retirement in the mid-2000s. We are very proud of him and his career at TI, so we designated this prize in his honor to recognize top senior design projects.

Eligibility for entry is relatively simple:

- You must have used at least three TI analog components, or one of TI's digital components plus two analog components.
- You must have completed the project with a working prototype.
- You must submit a project report to TI discussing the problem, solution and results, and include a list of TI components and how they were used.

There is a chapter in this book that goes into further detail about how to write an Engibous Prize entry.

With that, I will offer a biased hint: It is okay to use more than three TI devices. With more than 40,000 parts available to you, you should be able to find more than three that fit your needs.

Book organization

It's time to get started picking the best TI parts for your project. Here is a quick list of chapters:

- Analog:
  - Amplifiers.

    - Data converters.
    - Power management.
    - Wireless conductivity.
    - System components.
    - Interface components.

- Embedded processors:

    - MSP430™ ULP microcontrollers.
    - TMS320C2000™ microcontrollers.
    - ARM M3/M4 microcontrollers.
    - DSP and ARM microprocessors.

- Writing the project summary.

Each chapter will cover three topics:

- Technical overview.
- How to read the data sheet.
- How to pick the right part.

The last chapter will discuss the Engibous Prize in more detail. It will also introduce you to Tom Engibous and his career at TI and provide the official rules.

Analog
This module is the introduction to the analog section of the senior project book.

Introduction

Your senior project will require a lot of analog circuits. The goal of this section of the book is to help you find the right parts for your design. Texas Instruments has tens of thousands of unique part numbers covering this broad area of IC technology.

Reading the chapters that follow will help you remember the theory behind selecting the parts you will need. Our goal is to help you think through the process of selecting the right parts, and then actually finding them.

Here are the topics of the chapters in this section, with the authors' names in parentheses:

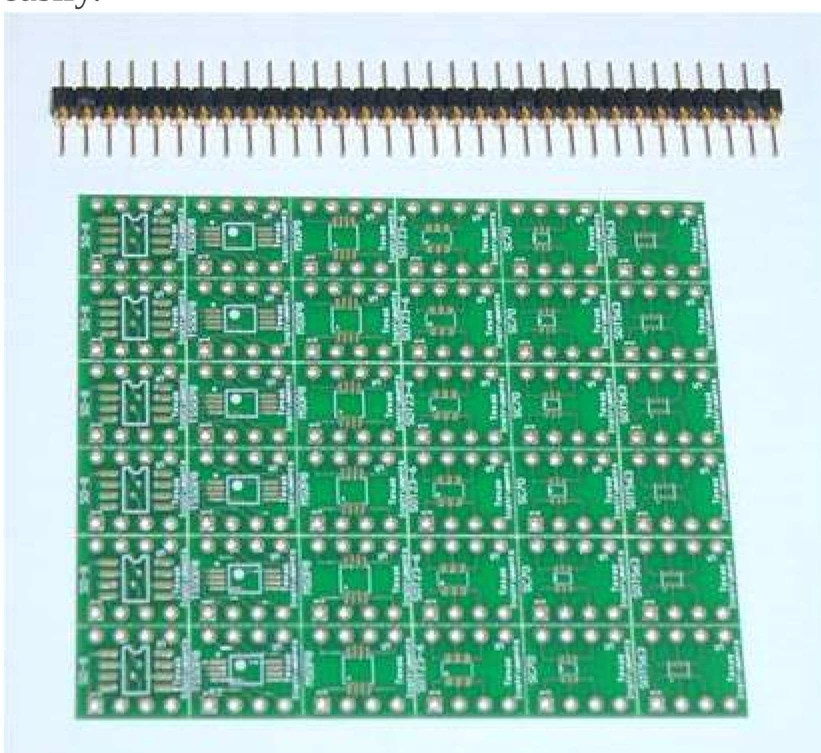
- Operational amplifiers (Bruce Trump).
- Data converters (Rick Downs and Tom Hendricks).
- Wireless communication devices (Thomas Almholt and Farrukh Inam).
- Interface devices (Thomas Kugelstadt).
- System devices (Charles Hefner).
- Power management (Upal Sengupta).

Packages

You may notice that many of the devices you would like to use from TI will not be easy to insert into your printed circuit board. And because they are not dual inline packaged (DIP), they don’t plug into a prototyping board. This is an issue we discussed at length when we were selecting parts for the Senior Project Cabinet. We decided to go this route because when you get to your first post-collegiate project, these difficult-to-solder parts will be what you'll design with, as they take up less board space and are easier to use in automated production lines. It is also less expensive to use these smaller devices. So we chose to give you a bit of experience using these devices and prepare you for the future.

But the news isn't all bad. There are adaptor boards available that will convert the quad flat package (QFP) to a DIP. One of them is shown in Figure 1.

Figure 2 shows an alternate solution that allows you to build your own adaptor boards. It has multiple adaptor circuits on one board that split apart easily.



Enough about adaptors. It’s time for you to jump into the chapters on analog circuits. Each was written by an expert on TI’s application staff. Learn to enjoy the task of revisiting material you forgot right after the test. This will not be the first time you will relearn material, or in some cases

learn it for the first time. It will be a career-long exercise as you grow with the technology.

Operational Amplifiers

This module reviews the concept and usage of the operational amplifier (op amp). It is aimed at the senior who is facing the task of choosing the right operational amplifier for their senior project. The module reviews the concepts of the op amp, how to read the data sheet (with keywords defined) and some suggestions on how to pick the right op amp for your project.

Operational amplifiers and other analog components

The op amp is perhaps the most versatile building block for analog circuits. With an op amp and a few passive components, you can make amplifiers of all sorts with inverting and noninverting gains. You can make integrators, differentiators, filters and voltage-level shifters. You can perform signal rectification, convert voltages to currents and vice versa. Applications information is widely available on Texas Instruments' website and across the Internet by searching with a few keywords.

Op Amps for Everyone is an excellent general reference. This section of the book will also briefly cover special amplifiers and related component types such as instrumentation amps, comparators and difference amps.

Let's start with some basics. If you recall the ideal op amp assumptions, the most important are infinite gain and infinite input impedance. The infinite gain assumption can be troubling. Think of it this way: When negative feedback is connected from output to input, the output seeks a voltage that creates 0 V between the two input terminals.

In Figure 1, the noninverting input voltage is clearly defined; it’s 0 V connected directly to ground. The voltage at the inverting input is determined by the voltage divider formed by R1 and R2. The op amp (with its feedback network) performs a balancing act, driving the output to a voltage that will make V_X = 0 V. Any small deviation of V_X away from zero will nudge the output in the direction to regain balance at 0 V. Some simple nodal equations involving V_{IN}, V_O and V_X = 0 will yield the transfer function of this circuit.

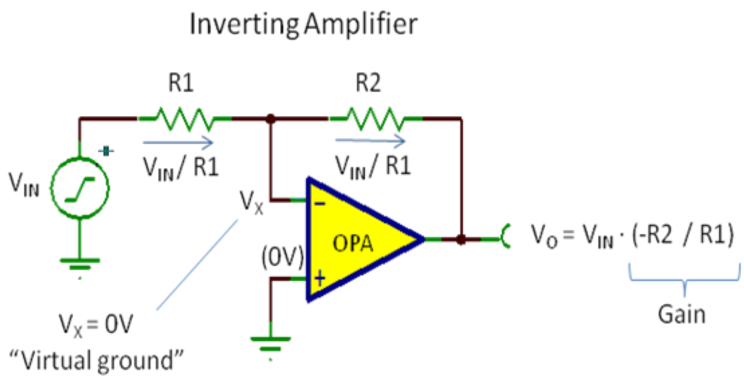


Figure 1.

The noninverting amplifier shown in Figure 2 is essentially the same circuit, with the input signal applied at a different node. The "input" side of R1 is now connected to ground and the noninverting input of the op amp is now the signal input terminal. Through feedback, the output seeks a voltage that causes the inverting input terminal voltage to be equal to V_{IN}. Again, simple nodal analysis will yield the transfer function and gain. Note that the gain is different in this case with a "+1" term added.

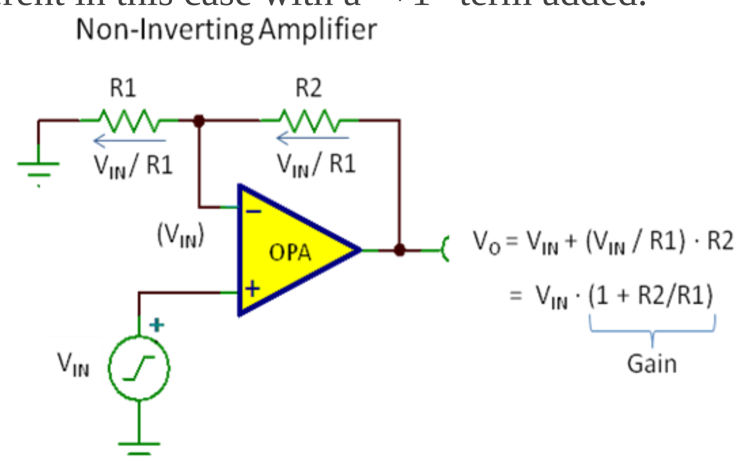


Figure 2.

Although many complexities exist involving the nonideal behavior of op amps, understanding an application circuit always starts with a firm understanding of how the ideal circuit is meant to operate.

Finding your op amp

You've probably used a prescribed op amp in your labs, and your professors have designed assignments to suit the characteristics of the op amp you are using. When you need to select an op amp that meets the needs of your

project, you will find that there are hundreds to choose from. Where do you start?

These key specifications are generally the most important selection criteria.

Operating voltage

- Battery-operated projects generally use CMOS op amps operating from 5 V or less.
  - Often use CMOS op amps operating from 5 V or less.
  - Rail-to-rail op amps allow wider input and output voltage with limited supply voltage.
- Higher voltages are often used for higher accuracy and special performance characteristics.
  - ±15-V supplies are commonly used for instrumentation and measurement applications.
  - Dual (±) supplies are easier when accurate positive/negative signals are important.

Gain bandwidth (GBW)

Determines the signal bandwidth that you can achieve with a given closed-loop gain (G).

- Maximum usable signal bandwidth = GBW / G.
- Op amps meeting minimum requirements will use less power.
- Op amps with unnecessarily high GBW (>50 MHz) may be more difficult to use.

Offset voltage (V_{OS} or V_{IO})

- The voltage between the two input terminals of the op amp (ideally zero).
  - Ranges from a few microvolts to a few millivolts.
  - Can be very important in processing accurate DC signal values.

    - Generally unimportant with AC signals such as audio.

- Offset at the output is amplified by the closed-loop gain.

Input bias current (I_B)

- The current that flows in the input terminals of an op amp.
    - Ranges from picoamps to microamps.
    - CMOS and JFET op amps have the lowest I_B.
- Contributes to offset voltage by I_B x Input Resistance.

Quiescent current (I_Q)

- The current drawn from the power supply with no load current.
- Ranges from approximately 1 microamp to several milliamps.
- Low I_Q op amps are "slow" for low-bandwidth signals, battery-powered circuits.

Input common-mode voltage range and output voltage range

Among the most common difficulties users encounter are the limitations to input voltage range and output voltage swing. So-called "rail-to-rail" types have an input voltage range that extends to, or slightly beyond, the power supply rails. Those featuring a rail-to-rail output can swing close to the power supply rails. Rail-to-rail amplifiers are particularly useful in battery-operated circuits with low-voltage supplies.

Dual and quad versions, package types

Many op amps are available in single, dual and quad package versions. Dual and quad versions can save space (and money, if you are concerned about high-volume production). In a prototype development, however, single op amps make circuit board or prototyping easier.

There are many different package types. Newer, tiny surface-mount types may be difficult to handle in prototyping. Some new op amp types may not

be available in the dual-inline (DIP) packages that are most convenient for prototyping.

Reading the data sheet

An op amp data sheet can be a bit overwhelming – so much information for a device with only five pins. The summary of features and suggested applications on the front page tell you much about the intended uses of the device. You should have a clear idea of the key specifications that will drive your selection. Be aware of the conditions that apply to each parameter. Ones that apply to all parameters may be listed at the top of the specification table. Others for individual parameters may be listed in the "conditions" column. Understand that these conditions may be a formal way of defining how we measure a parameter, but may not preclude use in other conditions.

Typical performance graphs can tell you much about the basic nature of a device. This information is not generally assured by production testing and may vary from device to device. You will find some graphs, such as open-loop gain vs. frequency, in virtually every op amp data sheet. Other graphs will vary according to the behavior of that particular device and its expected uses.

The applications discussion can be quite helpful. It provides cautions and advice on how to best use the device. Application figures and diagrams can help explain best practices and how to get the most out of a particular op amp. Much of an op amp users' design knowledge comes from careful reading of data sheets.

Finding your op amp

Consider the op amps on the recommended list first. These devices cover a wide range of needs and have proven to be easy-to-use, capable performers. A variety of package types is available. DIP packages are easy for prototypes. Surface-mount types can be awkward for manual construction but do save space. You are not limited to these devices if you have special needs. There is a selection tool on our website that provides slider-bar

tuning specifications. Go to http://www.ti.com/ and select Amplifiers and Linear.

Simulating with SPICE

You can download SPICE macromodels from http://www.ti.com/. They are found in the product folder for each device. Although you cannot simulate all components, such as data converters and controllers, simulating the critical analog portion of the signal chain does help solve basic problems and optimize your circuits. TI offers a free, easy-to-use SPICE simulation program with installed macromodels. Download it at http://www.ti.com/tina-ti.

Other amplifier types

There are a few other special amplifier types that deserve a brief introduction. You will find some of these devices in the TI recommended parts list.

Buffer amplifier. Increases the current output of an op amp to drive small speakers, motors, etc.

Difference amplifier. An op amp with four accurately matched resistors to measure voltage differences.

Comparators. Provide a binary output comparison of two analog voltages. Though some op amps can perform this function, comparators provide better features and performance.

Instrumentation amplifier. Three op amps and resistors to accurately acquire small-difference voltages in noisy environments.

Current shunt monitor. A special amplifier intended to measure current flowing in a shunt resistor, often used to measure current in a battery or power supply.

Programmable gain amplifier. Closed-loop gain is digitally controlled.

Current-feedback amplifier. A wide-bandwidth op amp similar to a standard op amp, with special restrictions on the feedback resistor values and configurations.

Voltage-controlled amplifier. Gain is controlled by an analog voltage signal.

You may also seek help on TI's E2E Community forums. The op amps are handled in the Precision Amplifiers forum. Please read this short primer on submitting questions before posting to ensure prompt and efficient support.

Data Converters

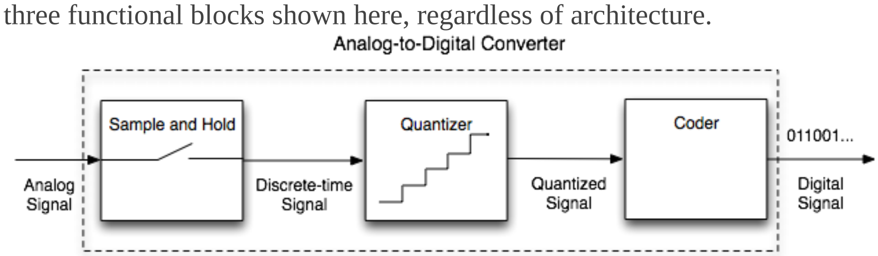
This module is a brief overview of how ADCs and DACs function, how to read an ADC or DAC data sheet, and how to pick the right one for some sample applications. This module is one of many in a textbook designed for seniors considering the use of TI products in their senior project.

Technical overview

A data converter is the bridge between the real, physical world of analog signals like voltage or current, and the digital world of numbers represented by ones and zeros. An analog-to-digital converter (ADC) converts a voltage into a number; a digital-to-analog converter (DAC) converts a number into a voltage or current. An ADC might be used to measure a weight or the intensity of light, or allow an audio signal to be captured and stored as a digital file for playback in a media player. Converting that digital file back into sound would require a DAC; a DAC can also control a valve that affects the flow of chemicals into a chemical reaction, or the position of a cutting head on a system that makes mechanical parts.

ADCs

Figure 1 is a general representation of an ADC. An analog-to-digital converter can be represented by the three functional blocks shown here, regardless of architecture.



Every ADC consists of three functional blocks: a sampler, a quantizer and an encoder. In some architectures, some of the functions may actually be combined, but each function is there nonetheless.

The **sampler** is responsible for sampling the input signal at a certain time; it is implied that this function also “holds” the signal constant for the converter to operate on it during its conversion time.

The **quantizer** is responsible for measuring the input signal and determining an output code level that most closely represents the voltage of the analog input. It approximates the sampled voltage with a level from a fixed set of 2^N possible voltage levels (where N is the number of bits of resolution), either via rounding or truncation.

The measurement of the input signal and creation of its corresponding output code are accomplished by comparing the input signal to a fixed **reference** voltage. The full-scale range (the maximum voltage that the converter can have on its input) is directly related to the reference voltage value. The minimum change in input voltage that the converter can detect is called the least significant bit (LSB) value. For example, if the full-scale range is the same as the 5-V reference voltage V_{REF}, and the converter has 12 bits of resolution, the LSB would be given by Equation 1:

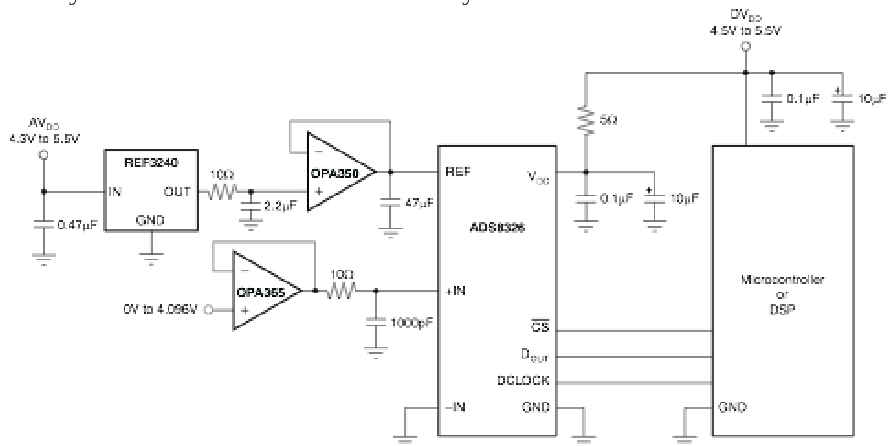
$$LSB = V_{REF}/2^N = 5\ V/2^{12} = 5\ V/4096 = 1.22\ mV \quad (1)$$

You can generally achieve the best conversion accuracy by matching the input signal range closely to the converter's full-scale range, either through amplification before the ADC or by changing the reference voltage to adjust the full-scale range.

The **encoder** can turn the internal code used by the quantizer into a more usable code for a system (for example, turning a thermometer code into a twos complement code) or can simply format the code into a

serial data stream for easy communication to a host processor.

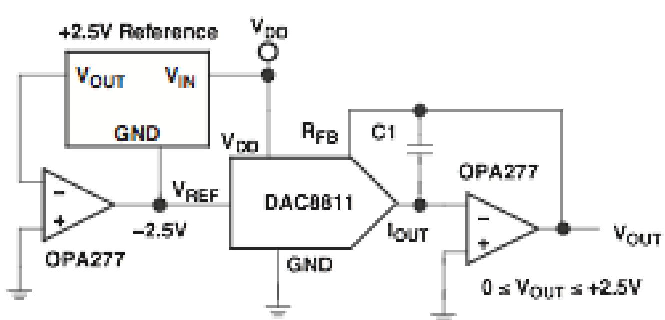
Figure 2 is an example of how an ADC is connected in a basic data-acquisition system (based on the ADS8326). The reference voltage is supplied by the REF3240; both reference and signal inputs are buffered by op amps. The ADC is supplied power, a reference voltage and the input signal voltage by analog circuitry; the digital interface to a host microcontroller or DSP is often a simple serial interface. High-speed applications may require more involved signal drive circuitry; the data sheet for most ADCs usually shows the recommended circuitry needed around the ADC.



DACs

A digital-to-analog converter block diagram would be similar to Figure 1, viewed from right to left: the DAC accepts a digital input, which is then decoded into a form that the DAC circuitry can use. The quantizer then creates a voltage or current corresponding to the digital input value. The sampler is not always on the analog side because most DACs have a means to latch the digital value provided by the interface.

While ADCs generally accept only voltage inputs, the output of a DAC may be a voltage or a current. Figure 3 shows an example of a multiplying architecture, which usually has a current output, using an external op amp to convert the current to a voltage. Many DACs provide this conversion circuitry in the device itself. Like the ADC, the DAC requires a reference input and may require analog circuitry on its output. The digital interface is not shown. This DAC8811 provides the current output, which is converted to a voltage through the output op amp and an internal feedback resistor.



How to read a data converter data sheet

As with any electronic component, the data converter data sheet is an essential resource. When deciding on a converter to use for a design, much of what you need to know is usually prominently displayed on the

first page of the data sheet. The most important parameters for a data converter are **speed**, **resolution** and **accuracy**.

Speed

For an ADC, speed refers to the time it takes to convert an analog input into a digital value – the actual specifications are acquisition time and conversion time, which when combined limit how fast the ADC can output a conversion result. This can also be expressed as throughput, which is usually shown as the maximum sampling frequency.

For a DAC, the limiting factor on speed is usually the settling time, which is the time it takes for the output to settle to a new value from a previous value within a specified error band. A 1-µs settling time implies that the converter may be suitable for updating its output at a rate up to 1 MHz.

Resolution

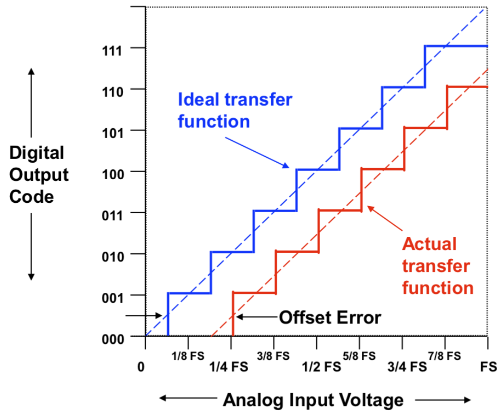
As described previously and with the example shown in Equation 1, resolution refers to the either the number of bits (N) that the converter has as its input or output, the number of counts or codes (which is simply 2^N), or the value of the least-significant bit in volts or amps. Higher resolution means that the converter can discriminate between smaller changes on the input signal or provide more precise control over an output signal.

Accuracy

Many people confuse resolution with accuracy. Just because you have a converter with 16 bits of resolution doesn't mean you always have 16 bits (or 15 ppm) of accuracy. Recall that a data converter requires a reference, and accuracy is the degree to which the result conforms to the correct value measured against a standard or reference. If you put exactly 1 V into an ADC and could resolve exactly that value with 16 bits, but the ADC tells you that it's 1.2 V, that's only 20 percent accuracy – a far cry from 15 ppm.

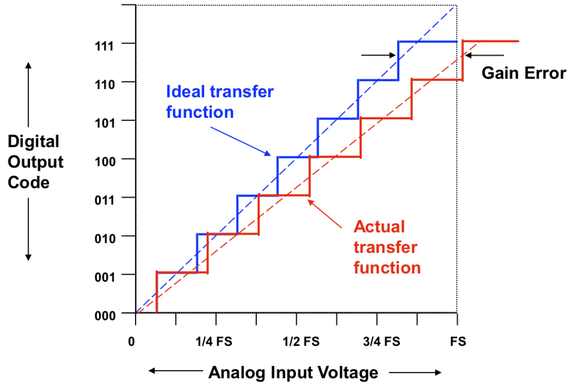
At a system level, the accuracy of the reference voltage will be one of the primary factors in the overall accuracy of the system. But the data converter itself contributes some errors. Some data converters will express an overall accuracy specification – often called total unadjusted error – but it is more common to see specifications for offset error, gain error and linearity.

The ideal transfer function for a data converter is shown in Figure 4, as a blue line. It appears as a staircase because the quantizer can only represent a range of voltages with a single code. The location of the transition point from one code to another is key to describing the converter's accuracy.



Offset error is the difference between the actual transition point and the ideal transition point – resulting in a translation of the transfer function left or right. Although this error is measured around a near-zero

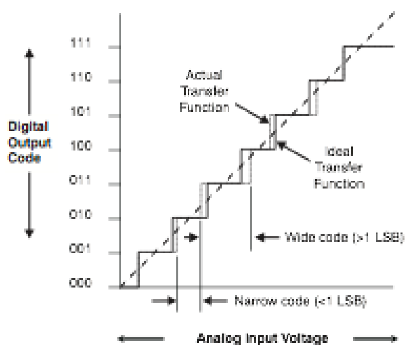
voltage input or output, the error continues throughout the entire transfer function from zero to a full-scale (FS) voltage. Consequently, the offset error near zero is the same as the offset error with a near FS voltage.



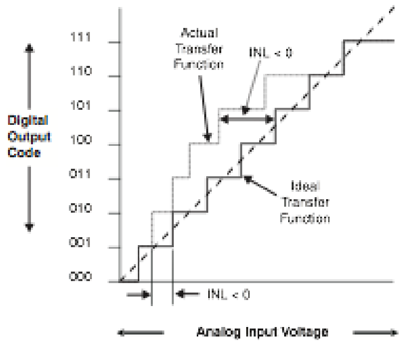
Gain error is the difference between the actual last transition point and the ideal last transition point – resulting in a rotation of the transfer function. It is the difference between the ideal slope of the transfer function and the actual slope between the measured zero point to FS, minus the converter's offset error. This is actually measured by looking at where the last transition point at full scale occurs, as shown in Figure 5.

As you might imagine from the use of the term "error," smaller gain and offset errors imply a more accurate converter. Gain and offset errors can often be corrected for in the digital domain, using the system microcontroller or DSP.

Linearity errors, on the other hand, are much more difficult to correct. While the transfer functions in Figure 4 and Figure 5 show steps that are exactly the same size, in actual converters the width of these steps will vary. Figure 6 shows how differential nonlinearity (DNL) is measured. DNL is the deviation in code width from the ideal 1LSB code width.



A DNL error less than –1 LSB can cause an entire code to "disappear," resulting in what is called a **missing code**. The smaller the range of the DNL specification, the better.



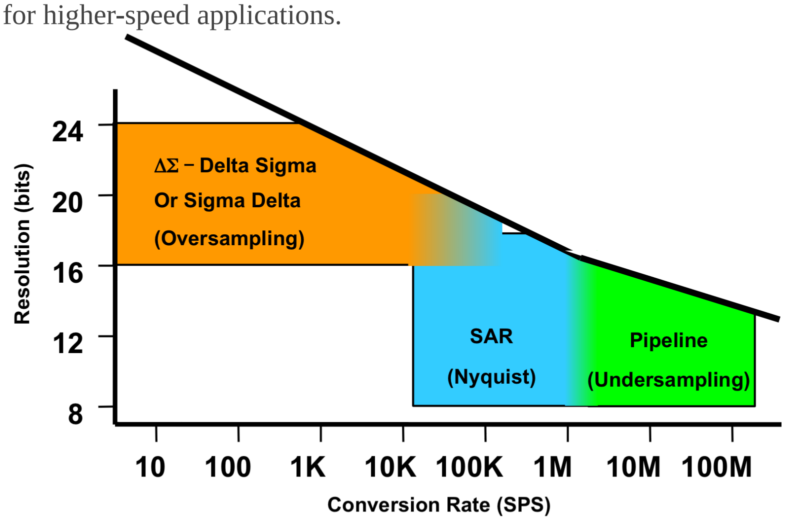
Integral nonlinearity (Figure 7) is the cumulative effect of all of the differential nonlinearity errors, and is the maximum deviation between the actual code transition points and the corresponding ideal transition points after gain and offset error have been removed. The smaller the INL specification, the more accurate the data converter will be.

Speed, resolution and accuracy are important considerations in selecting a data converter, and you will often find what you need to know about these on the front page of the converter data sheet. But other important factors, such as the details of the digital interface and mechanical drawings of the package, are further inside the data sheet. You need to read the entire data sheet to effectively use a data converter.

Choosing the right data converter

A multitude of data converters are available for your design. While the three main specifications of speed, resolution and accuracy will help in the final selection process, narrowing down the options to choose from is the first step.

When selecting an ADC for a particular application, a good first selection criteria is to look at the topology of the ADC. Figure 8 is a simple comparison of ADC architectures that can help you find the right place to start when selecting a converter for your application. Delta-sigma converters are most suitable for higher-resolution tasks, while successive-approximation-register and pipeline architectures are the ones to look to for higher-speed applications.



Digital-to-analog converters have similar trade-offs in architecture: delta-sigma DACs tend to be slower, while R-2R, string and multiplying DACs all provide good general-purpose performance. High-frequency, fast-settling DACs are generally for current-steering architectures.

Knowing the speed and resolution requirements of your application, you can anticipate which architecture of converter will most likely suit your needs. Then you can look more closely for the converter that matches the accuracy requirements and other features that the application demands.

Table 1 lists some applications where data converters are used, as well as the selection criteria and some examples of actual converter products suitable for those applications.

Application	**Required sample rate**	**Required resolution**	**Architecture**	**Example part**	**Comments**
Weigh scale	< 100 sps	18-24 bits	Delta-sigma	ADS1211, ADS1258	High accuracy
Temperature measurement	< 10 sps	8-18 bits	Delta-sigma	ADS1146	High accuracy
Waveform analysis/synthesis	< 100 Msps	8-16 bits	Pipeline	ADS6445, DAC2902	High speed and good linearity (low distortion) required
Test and measurement	< 1 Msps	12-24 bits	SAR ADC, multiplying DAC	ADS7824, ADS8326, DAC8820	High accuracy and throughput, multiple channels
Ultrasonic imager	<100 Msps	12-14 bits	Pipeline	ADS6445	High speed, good resolution
Software-defined radio	<500 Msps	12-14 bits	Pipeline	ADS5474, ADS41B49	High speed, good resolution
Motor control and positioning	<500 ksps	12-18 bits	SAR ADC, multiplying DAC	ADS8361, DAC8811	High accuracy and throughput, multiple channels

Wireless Communications
This module summarizes the various wireless communications products offered by Texas Instruments. It is specifically aimed at college seniors beginning their senior project.

Introduction

We first learned about the propagation of electromagnetic waves through the works of Maxwell and Hertz. Later, Tesla demonstrated the transmission of information using these waves, and in 1898, Marconi first demonstrated wireless communication from a boat to the Isle of Wight in the English Channel. In 1948, Claude Shannon's work established the possibility of error-free communication under restriction for data rate (R) and signal-to-noise ratio (SNR) in a digital communication system. Thus began the era of active research in information theory and channel coding, with the goal to achieve data rates at channel capacity (C) in a digital communication system.

Digital vs. analog transmission

Digital signals are easy to regenerate, as they operate in binary state. This is not true for analog signals, which have infinite states. A pulse in a digital system is affected by distortion because of frequency characteristics and noise present in the channel. Before it can degrade to an ambiguous shape, amplifiers in the transmission path restore the pulse shape to its original form and retransmit. Digital circuits are also more reliable and less costly to design. Digital hardware is flexible and reconfigurable via software and can accommodate the operation of different communication techniques on the same hardware. Digital techniques lend themselves easily to signal-processing functions that protect against interference and jamming and allow for encryption and information security.

Requirements for wireless systems

In wireless systems, different applications have different requirements in terms of range, data rate and mobility energy consumption, for example. A few of these are listed below.

Data rate

Sensor networks that monitor temperature, humidity, speed and acceleration usually require data rates from a few bits per second to about 1 kbps. The central node in a sensor network might require data rates as high as 10 Mbps, since its tasks are coordination and data gathering. Speech communication requires between 5 kbps and 64 kbps, depending on the fidelity and amount of compression. Cellular networks with higher spectral efficiency operate at 10 kbps, while high-speed data services like WLAN and 3G/4G can go as high as 100 Mbps or more by utilizing space and time diversity techniques.

Coverage and number of subscribers

The task of a communication system is to convey information at a distance (d) with minimum probability of error (Pb) using a minimum amount of transmit power. In a mesh network, the coverage area of a system can be made independent of the range by adding multiple base stations. In sensor networks, nodes can be converted to routers that can communicate with the coordinator nodes over multiple hops.

Fixed or mobile installation

Wireless systems are designed to operate in mobile environments; this incurs costs in terms of system performance, as channel effects such as multipath (fading) and speed of mobility (Doppler shifts) can degrade bit-error-rate performance and reduce channel capacity.

Power consumption

Wireless devices are battery-operated and designed to consume a minimum amount of power. This allows longer battery life and fewer recharge cycles. In limited energy scenarios, power-efficient modulation schemes are used, along with control hardware, to regulate power consumption during the transmission and reception of packets. Control hardware puts radios in low-power modes during inactive periods.

Spectrum utilization

Frequency spectrum is a natural resource; its efficient use is stipulated by regulatory authorities. A radio service provider can buy or lease a portion of the spectrum, where it can have complete control over its operations. Alternatively, a portion of the spectrum can be allocated to a service, such as a cordless phone, where users can then set up hardware for that service without needing a license. The industrial, scientific and medical (ISM) bands are license-free bands where proprietary communication techniques can be used to implement wireless services.

In multiple user environments, multiple access schemes are employed. These can be implemented in the following ways. Frequency-division multiple access (FDMA) allocates bandwidth to users in a frequency spectrum, where they can operate in specific frequency bands. Time-division multiple access (TDMA) is based on time-slicing the occupied spectrum and creating a schedule of when each pair of radios is on the air. Code-division multiple access (CDMA) is a spread-spectrum technique where each user is provided with a unique uncorrelated pseudo-random noise (PN) sequence (code) that can be used to despread the received signal before demodulation. The main advantage of CDMA over either FDMA or TDMA is that the frequency reuse factor is 100 percent. This means that the entire allocated frequency band can be used for transmission. Frequency reuse in FDMA and TDMA systems depends on the isolation between areas of operation, depending on the path loss of the radio channel. CDMA can reuse the allocated spectrum for all areas.

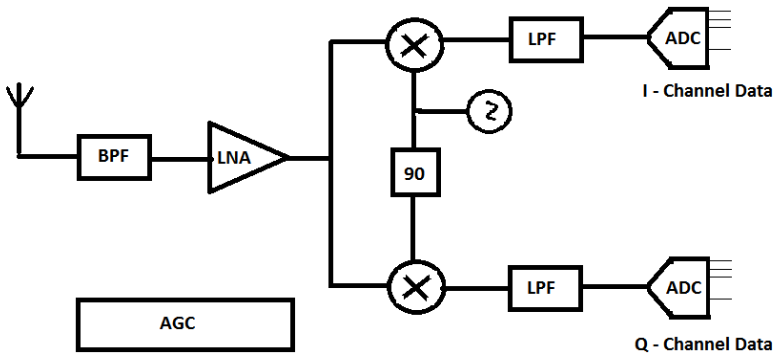
Blocks of a wireless communication system

To simplify the drawings, let's split a typical transceiver into its two major components, the receiver and transmitter, and describe them individually.

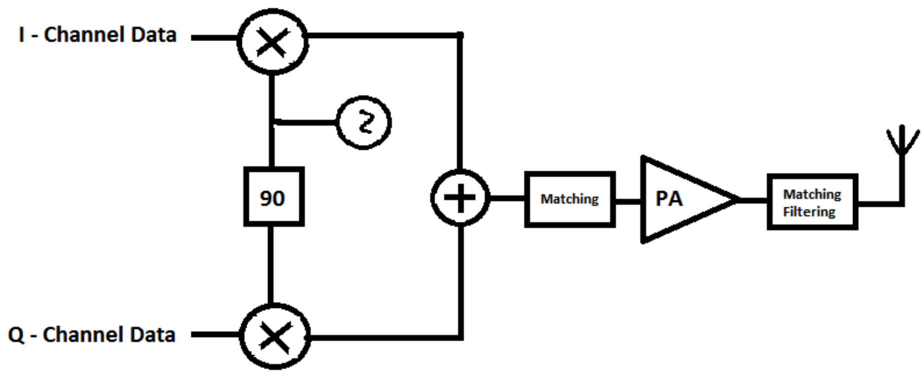
Block diagram of a receiver

Figure 1 is a system block diagram of a direct conversion receiver and transmitter. An antenna is followed by a bandpass filter, used as a band select filter. This eliminates out-of-band noise and presents the signal to the low-noise amplifier (LNA). The LNA then amplifies the desired signal, adding a minimum amount of inherent noise. The signal processed by the LNA is then down-converted to the desired IF frequency by a set of mixers

operating in quadrature. These mixers are often image-reject mixers and have some gain as well. After down-conversion, the low-frequency IF signal is lowpass-filtered to remove aliasing components and converted to digital samples by the analog-to-digital converter. In the digital domain, more filtering is applied for channel selection, and plenty of signal processing is performed to remove any channel effect before the detection stage.



On the transmitter side, the digital I and Q data – which are already processed by a digital-to-analog converter, filtered and amplified – are up-converted by quadrature mixers to the carrier frequency of interest. After combining, the signal is again filtered to contain the spectral content of the signal in the required bandwidth stipulated by the emission mask. After that, it is applied to the power amplifier and transmitted over the air with an antenna (Figure 2).



Now let's get into the details for each of the blocks in the transmitter and receiver.

Antennas

Antennas are coupling circuits to space that radiate or receive information-bearing electromagnetic waves. In a receiving antenna, the EM wave impinging on the surface produces currents, which in a 50-ohm system are applied to an LNA for amplification and subsequent processing. On the transmitter side, the surface current density on the antenna produces a magnetic field around the antenna. If the current density is time-varying, an accompanying electric field is also produced; propagation takes place in a direction perpendicular to both the electric and magnetic fields. The total radiated power is given by a surface integral of the Poynting vector over any surrounding surface. The value of resistance that would dissipate this amount of power is called the radiation resistance, which is caused by the power radiated. The total resistance of the antenna comprises radiation resistance and resistance due to power loss. For high efficiency, the value of radiation resistance should be large.

Filters

Filters remove the effect of broadband noise and thereby increase the SNR of a desired signal. They are also used to select channels in multiple transmission environments and to remove image frequencies in broadband services and other out-of-band interference. In the transmitter, digital pulse-shaping filters are used for efficient utilization of the RF spectrum and externally to suppress RF splatter in adjacent channels.

Amplifiers

The RF signal at a receiver's antenna is very small in magnitude. The IEEE 802.15.4 standard defines a minimum signal of -85 dBm = 3.16 pW, whose voltage in a 50-ohm system is 12.6 μV. At the detector, the typical signal requirement is at 1 mVp-p for detection and decoding of digital waveforms. To achieve this, low-noise amplifiers are used in the front end to amplify the signal up to the detection stage. The gain required in the receiver is usually between 60-90 dB – very high. Therefore, to avoid oscillations, this gain is distributed over different stages of the radio-frequency integrated circuit.

On the transmitter side, power amplifiers (PAs) are used to transmit the EM wave. PAs come in various classes and can be linear and nonlinear. They

usually employ matching circuits between the output and the load. In practice, the output impedance of the active device is complex and varies with load; thus nonlinear complex impedance must be matched to a linear load. More often, the antenna impedance may be complex and vary with both the position of the transceiver and surrounding objects. This makes PA input and output matching a nontrivial task. In practice, a technique called load pull is applied to a matching circuit design. In this test, the output power is measured and plotted as a function of the complex impedance load seen by the transistor output stage. A tuner can accurately vary the output impedance while a power meter measures the power, keeping it constant. The impedance gives a contour on the Smith chart. As the output impedance varies, this changes the input impedance of the transistor, thus requiring the use of a second tuner such that the impedance seen by the generator remains constant.

Mixers

Mixers are fundamental building blocks that translate frequencies from one band to another for further processing without changing the information content. On the transmitter side, they up-convert a baseband signal for efficient transmission over a channel. At the receiver, they down-convert to a suitable intermediate frequency for the extraction of information. The frequency translation occurs with the help of an oscillator and RF signal applied to a strong nonlinearity and then filtering of the desired frequency band.

Oscillator

Oscillators produce sinusoidal signals that up-convert or down-convert an RF signal to the required frequency, where subsequent processing might begin. They are designed to operate at a specified frequency. Generally, there is an amplifier and feedback circuit that returns a portion of the amplified signal back to the input. When feedback is aligned in phase, sustained oscillators occur. In practice, they are not perfect, and drift in frequency from time to time. They are also susceptible to phase noise. Due to this, many transceivers operate them in a phase-locked loop (PLL) that can provide frequency stability and lower phase noise. Oscillators use an external crystal to provide a reference signal to PLL-based signal sources.

The accuracy of the crystal is specified in ppm. Crystal accuracy is important because the transmit or receive bandwidth may have to be changed according to the drift in the crystal frequency.

Analog-to-digital converter

Analog-to-digital converters are required to convert analog signals to digital signals for baseband processing. After digitizing, signal channel selection can occur in the digital domain, as can equalization.

Transceiver system parameters

This section identifies concepts essential to understanding and evaluating an RF system. The information on these parameters is available in the product's data sheet. Understanding the data sheet is key to integrating efficient communication systems.

RF communication range

Receiver sensitivity, transmitter output power, signal frequency and propagation environment determine how far apart the receiver must be from the transmitter for error-free communication. A complete expression encompassing these paramaters is given by the Friis equation, Equation 1:

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \; (Watts)$$

With isotropic antennas in free space, the signal power at distance d can be calculated with a path loss equation (Equation 2):

$$P_r = P_t - 10n\log_{10}(f) - 10n\log_{10}(d) + 30n - 32.44$$

Where:

Pt = the signal power in dBm at distance d

L = overall system loss

λ = wavelength

Pr = the signal power at the antenna

f = the signal frequency in MHz

d = the distance in meters from the antenna

n = the path loss exponent whose value is determined experimentally and varies under different propagation environments

For example, the required sensitivity of a ZigBee device operating at 2.4 GHz is -85 dBm. Assuming isotropic antennas with unity gains and ideal line-of-sight conditions and a transmit power of 1 mW (0 dBm), the maximum separation between the radios can be approximately 175 m. Increase the power by 6 dB, however, and the range approximately doubles, to 350 m.

Receiver sensitivity

Noise is a phenomenon that degrades signal quality and impairs the receiver's ability to make correct decisions about symbol detection. Thermal noise is a zero-mean Gaussian random process and processes the same power spectral density for all frequencies of interest. It is superimposed on a signal as it travels through the communication chain, and therefore has an additive effect. It is thus commonly referred to as additive white Gaussian noise (AWGN). The power spectral density of double-sided white noise is N0/2. At room temperature, single-sided noise power spectral density in the 1-Hz bandwidth is calculated with Equation 3:

$$N_0 = \kappa T = 1.38 \times 10^{-23} (W/{}^{o}K.Hz) \times 290^{o} (K) = 4 \times 10^{-18} (mW/Hz)$$

The signal at the receiver is very small in magnitude and must be amplified before any meaningful information can be extracted from it. This is done using high gain amplifiers at the front end. The amplifiers also amplify noise and interference already present in the signal, and might even add their own noise to the processed signal. Such broadband noise is another reason why bandpass filters are used in the front end of a receiver. They attenuate out-of-band noise while keeping the signal of interest unchanged, thereby increasing the SNR.

Receiver sensitivity is the weakest RF signal that can be processed to develop a minimum SNR for achieving the required bit-error-rate (BER) performance. In AWGN, the sensitivity of a receiver can be derived from its noise figure. The noise factor of a receiver from the antenna port to the output of a detector is expressed in Equation 4 as the ratio of the SNR at the input to the SNR at the output.

$$F = \frac{SNRin}{SNRout}$$

Noise figure is a measure of how much a system adds noise to a signal as it passes through it. It is given by 10 * log(F)(dB). Assuming that minimum SNR is required for obtaining the defined error rate, the corresponding sensitivity level is calculated with Equation 5:

$$Pmin = -174 + 10\log(B) + NF + SNRmin$$

Where:

10 log(kTo) = -174 dBm/Hz is from (2.8)

Receiver noise bandwidth B is in Hz

NF = the overall noise figure of the receiver in dB

Data sheets specify this quantity for a specific bandwidth and BER performance. Therefore, it is often advantageous to use the smallest possible data rate in order to be able to use the smallest possible receiver bandwidth. Consider a Wi-Fi device with -83 dBm input sensitivity, a ZigBee at -97 dBm and a narrowband radio (CC1120) at -123 dBm.

From the Friss equation, you learned that for about every 6 dB in output power or input sensitivity, the range of the wireless system doubles. Therefore, a 40-dB improvement will equate to approximately 100 times the range.

Adjacent channel selectivity

Many different users must be able to broadcast at the same time. This necessitates separating the desired transmission from all the others at the receiver. One standard method is to allocate different frequency bands to various users; signals from different users can be separated using bandpass filters. Practical receive filters do not completely attenuate the frequency content of out-of-band signals, nor do they pass in-band signals completely distortion-free. Therefore, there is a requirement on the transmitters to spill the least amount of power in the adjacent bands.

This value is typically measured by applying a signal 3 dB above the sensitivity level of the system, adding a blocking signal in the adjacent channel, and increasing the power of the blocker until the receiver BER becomes the same as measured with 3 dB less signal and no blocker.

Maximum power is limited by nonlinearities

The building blocks of a receiver generate harmonics (tones at an integer multiple of the fundamental frequency) due to nonlinearities. This causes the translation of out-of-band frequencies onto in-band channels, thereby degrading SNR.

Harmonic distortion is the ratio of the amplitude of a particular tone to the fundamental. It is usually not a problem in a receiver and can be filtered out after the LNA. Cross-modulation occurs when a strong interferer and a weak desired signal present themselves at the front end. Amplitude modulation on the strong interferer is transferred to the desired signal through interaction with a receiver’s nonlinearity. A figure of merit of a receiver is the 1-dB compression point, P1dB, where the gain of the system is reduced by 1 dB as input power increases. Receiver sensitivity and the input 1-dB compression point set the dynamic range of a receiver.

Multitone distortions

Intermodulation distortions arise when more than one tone is present at the input. The third-order intercept point (IP3), which is measured by a two-tone test, shows to what extent the receiver can handle an environment with strong undesired signals. Second- and third-order intermodulation products are problematic in a receiver, as they fall very close to its operating

frequency. The amplitude of the fundamental signal increases in proportion to the input signal, whereas the third-order intermodulation product increases as a cube of the fundmental. The IP3 is defined as the intersection of two lines in Figure 3 below.

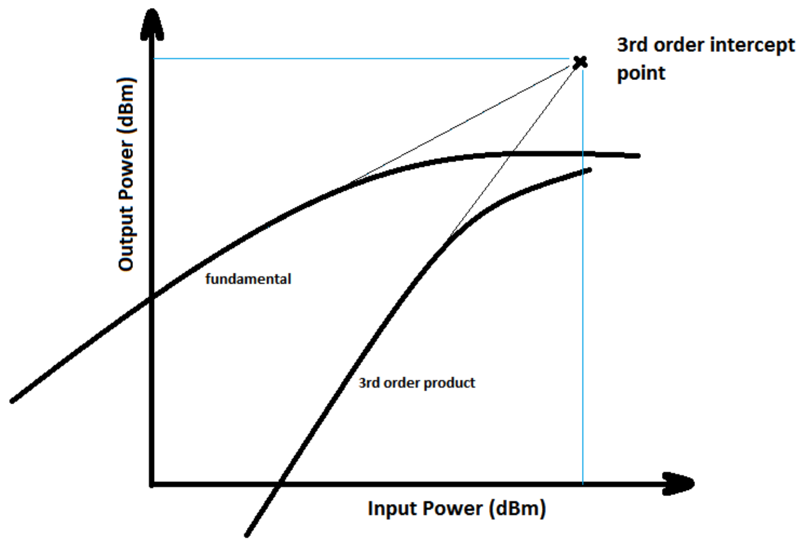


Figure 3

Wireless systems operate in an environment where they encounter strong interfering signals from other transmitters. Since a large signal tends to reduce the average gain of the circuit, the weak signal may experience a diminishingly small gain. This is called desensitization, and for a large-enough interferer, the gain for the weak desired signal goes to zero and the signal is blocked.

An interferer that desensitizes a circuit even if the gain doesn't go to zero is called a blocker. Receivers must be able to withstand a blocking signal 60 to 70 dB greater than the desired signal. This information is specified in data sheets as adjacent and alternate channel-rejection performance of radio-frequency integrated circuits.

Conclusion

TI's wireless technology boasts a range of products, from low-power applications to cellular baseband processors. In low-power applications, TI

has a broad range of devices that can suit any application, from consumer/personal networking to industrial monitoring and asset tracking. TI can provide complete solutions with reference designs, hardware development kits and software to jumpstart any wireless project, ranging from sub-1 GHz to ZigBee low-power networking and the Internet of things.

A few of TI's products for low-power wireless applications are listed in Table 1.

Table 1. TI Products for low power wireless applications.

Technology								
Frequency range	**Under 100MHz**	**100MHz - 1GHz**	**100MHz - 1GHz**	**2400-2500MHz**	**2400-2500MHz**	**2400-2500MHz**	**2400-2500MHz**	**2400-2500MHz**
Description	RFID / NFC transceiver	Sub 1GHz transceivers and SoC's	Sub 1GHz transceivers and SoC's	Proprietary 2.4Ghz transceivers and SoC's	Zigbee transceivers and SoC's	Single mode Bluetooth SoC	Class 2 HCI Module	Low latency wireless audio devices
Data Rate	1.6-848kbps	1.2-500kbps	1.2-100kbps	1.2-500kbps	250kbps	1Mbps	2.1Mbps	5Mbps
Maxium Application Level Data Rate	848kbps	~400kbps	~50kbps	~400kbps	~50kbps	~100kbps	2.1Mbps	~4Mbps
Tramsmit Output Power	23dBm	10dBm	15dBm	0dBm	7dBm	4dBm	10dBm	5dBm
Best Receiver Sensitivity	848kHz, 2.1mVpp	- 110dBm	-123dBm	-108dBm	-97dBm	-93dBm	-93dBm	-83dBm
Standby current consumption	1.9mA	1uA	1uA	1uA	1uA	1uA	135 uA	1uA
Active mode current consumption	~120mA	~20mA	~45mA	~20mA	~30mA	18.2 mA (0dBm)	40 mA (TxEDR)	~30mA
Range	~1 inch	~1000 feet	~10000 feet	~30feet	~100feet	~100feet	~100feet	~100feet
Part Numbers	TRF7970A	CC1101 / CC430x / CC11xL	CC112x / CC1200	CC2500 / CC2510	CC2520 / CC253x	CC254x	CC256x	CC85xx

Wireless Communications background
This module looks at the basic concepts of wireless communications. It is one of many modules in a textbook created for college seniors to help them select the best components for their senior project.

Basics of digital communications

Communication theory aims to explore and develop methods that suppress (as far as possible) the effect of noise and to simultaneously transmit as many discrete signals as possible through a channel. Spectral analysis is a tool that connects time-domain signals to the frequency domain, allowing insight into the characteristics of broadband and narrowband signals in a communication bandwidth.

Spectral analysis

Frequency has a ubiquitous role in the process of communication. It is used as a carrier and bandwidths are specified in terms of it. It is therefore important to have tools with which you can easily determine the frequency content in a signal. This can be achieved using the Fourier transform (FT) and its discrete counterpart, the DFT. The FT of a signal $w(t)$ is defined in Equation 1 as:

$$W(f) = \int_{-\infty}^{\infty} w(t)\exp(-j2\pi ft)dt$$

Its inverse is calculated with Equation 2:

$$w(t) = \int_{-\infty}^{\infty} W(f)\exp(j2\pi ft)df$$

The above equations show that $w(t)$ is a weighted sum of sinusoids in the interval -∞ to $+\infty$. The weights are complex numbers $W(f)$. If at any particular frequency the magnitude spectrum is strictly positive, then that frequency is said to be present in $w(t)$. The set of all frequencies present in a signal is its frequency content. If this content consists of frequencies in a certain range, then $w(t)$ is said to be bandlimited with a certain bandwidth.

Digital modulation

It is the process of converting digital symbols into waveforms that are compatible with the characteristics of the transmission medium. In the case of baseband modulation, these waveforms take the shape of pulses designed to reduce intersymbol interference (ISI). In the case of bandpass modulation, these shaped pulses modulate a sinusoidal carrier wave that is converted to an electromagnetic (EM) field for propagation over distances. In free space, antennas radiate and receive EM signals. Antennas operate effectively only when their dimensions are of the order of magnitude of quarter wavelength $\left(\frac{\Lambda}{4}\right)$ of the transmitted signal. If the signal frequency is very high, antenna dimension becomes practical; however, high frequencies get attenuated by the atmosphere and therefore cannot travel great distances.

Basic modulation techniques

Any message can be converted into binary digits called bits. For transmission, these bits are grouped together and encoded into sequences whose elements are the symbols of an alphabet set. To utilize bandwidth more efficiently, these alphabets are encoded in waveforms called pulses, which are then combined to form a baseband signal. For example, bitstream 0100100101001011101010 1 can be paired as 01 00 10 01 01 11 and so on. Then the pairs can be encoded as -1, -3, 1, -1, +3 and so on to produce the symbol sequence. There are many ways to map from bits to symbols. Bitstreams can be mapped to eight-level, 16-level, 256-level, etc. After the original message is grouped into alphabets, it must be turned into analog waveforms by choosing a pulse shape $\mathrm{p(t)}$ and then transmitting $–\mathrm{p(t - kT)}$, -3$\mathrm{p(t – kT)}$, $\mathrm{p(t – kT)}$, -$\mathrm{p(t – kT)}$, $\mathrm{3p(t –kT)}$. In general, this four-level signal takes the form shown in Equation 3:

$$\mathrm{d(t)} = \sum_{\mathrm{k}} I_k \mathrm{p(t - kT)}; I_k \in \{\pm 1, \pm 3\}; \mathrm{k} = 1, 2, \ldots$$

Where:

$\mathrm{d(t)}$ = an analog waveform consisting of pulses at symbol time kT and the amplitude of the pulse is proportional to the associated symbol value.

Ideally, the pulse should be chosen so that the value of message at k does not interfere with the message at any other time (no ISI) and makes efficient use of bandwidth.

ISI can manifest itself in two ways: when the pulse shape $\mathrm{p}(\mathrm{t})$ is wider in time than a single symbol time interval T, and when the pulses experience channel distortions and multipath fading effects.

Consider a two-level system in which $s_0(\mathrm{t})$ and $s_1(\mathrm{t})$ are finite energy signals representing logical 0 and 1, respectively. These signals can be of any shape but must have finite energy in the signaling interval. Then you can construct a framework of representative basic modulation schemes. Some fundamental digital modulation schemes are below.

Amplitude shift keying

In amplitude shift keying (ASK), the information is conveyed by varying the amplitude of a carrier wave in accordance with the symbol stream. ASK can be expressed as Equation 4:

$$s_k\ (\mathrm{t}) = I_k \mathrm{p}(\mathrm{t})\cos(w_0\ \mathrm{t}+\Phi);\ I_k \in \{0,1\};\ 0 \leq \mathrm{t} \leq \mathrm{T};$$

In Equation 4, the phase term is an arbitrary constant. Binary ASK signaling, also called on-off keying, was one of the earliest forms of digital modulation used in radio telegraphy. ASK has a high peak-to-average ratio and is no longer widely used; however, TI’s low-power wireless radio-frequency integrated circuits support this modulation scheme for various data rates in sensor applications. Figures 1 - 4 shows waveforms for Amplitude Shift Keying.

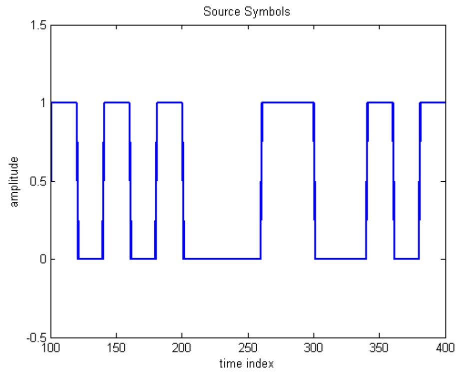


Figure 1. Amplitude Shift Keying source symbols.

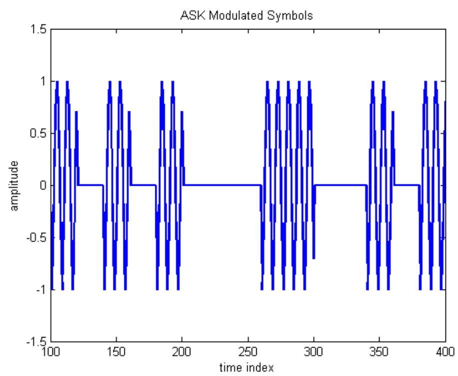


Figure 2. Amplitude Shift Keying modulated symbols.

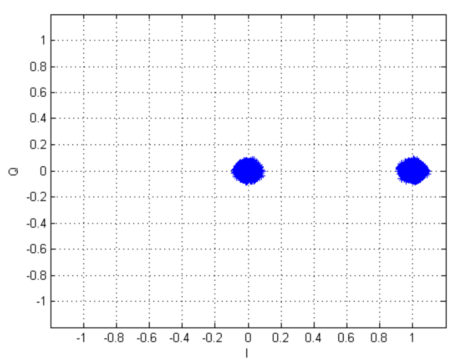


Figure 3. Amplitude Shift Keying constellation plot.

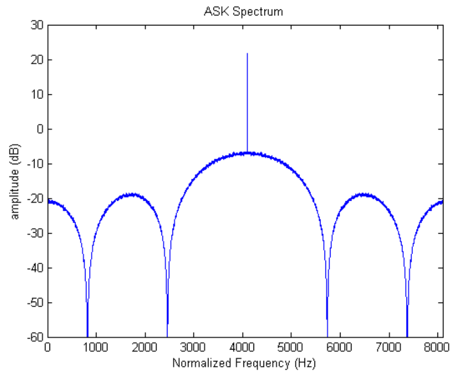


Figure 4. Amplitude Shift Keying spectrum.

Frequency-shift keying

The general analytical expression for frequency shift keying (FSK) is given in Equation 5:

$$s_k\ (\mathrm{t}) = A\cos(w_0\mathrm{t}+2\pi I_k\Delta \mathrm{ft}+\Phi);\mathrm{k} = 1,\ldots \mathrm{M};0\leq \mathrm{t}\leq \mathrm{T}$$

Where:

The frequency Δf = the amount of shift in the carrier frequency corresponding to the alphabet I_k ε{±1, ±3. . .,±M}

Phase term is an arbitrary constant.

The FSK waveform sketch in the following figures show typical frequency changes at the symbol interval. The change from one frequency to another can be rather abrupt; this gives rise to spikes in the spectrum of FSK. The minimum required bandwidth for orthogonal FSK signals for coherent detection is 1/2T, whereas for noncoherent detection the bandwidth is 1/T. FSK does not have constellation plots because of constant rotation of the signal vector in the IQ plane. Figures 5 - 7 are typical waveforms for FSK.

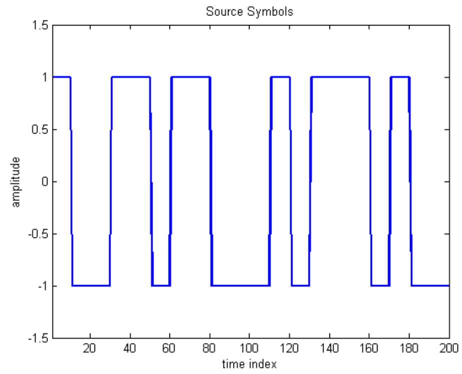


Figure 5. Frequency Shift Keying symbol source.

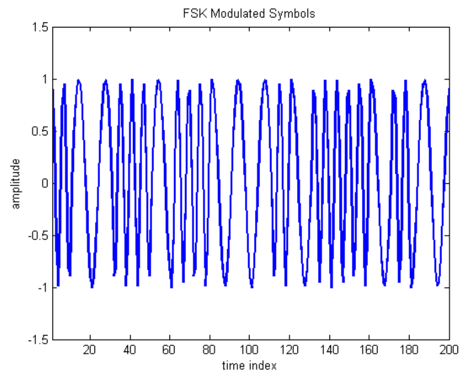


Figure 6. Frequency Shift Keying modulated symbols.

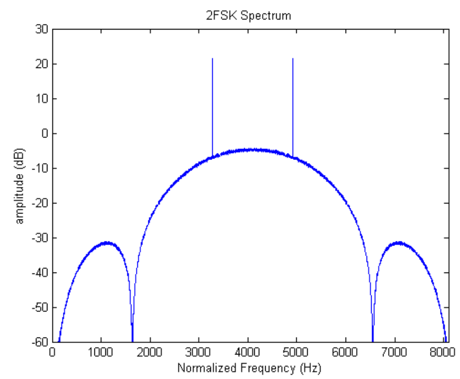


Figure 7. Frequency Shift Keying spectrum.

Phase-shift keying

Developed the during early days of the space program, phase-shift keying (PSK) is widely used in commercial satellite links. The general expression

for PSK is shown in Equation 6:

$$s_k(t) = p(t)\cos(w_0 t + \Phi_k); k = 1,\ldots,M \; 0 \le t \le T$$

Where the phase term Φ_i will have M discrete values typically given by Equation 7:

$$\Phi_k(t) = \frac{2\pi k}{M} \; k = 1,\ldots M$$

In the basic case of binary PSK, the modulating data signal shifts the phase of the waveforms to one of two states: either zero or π. The waveform sketch in the figure shows abrupt phase changes in the signaling interval. Figures 8 through 11 are typical waveforms for a PSK modulation system.

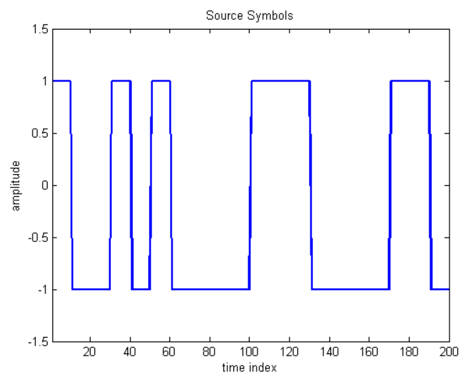


Figure 8. Phase Shift Keying symbol source.

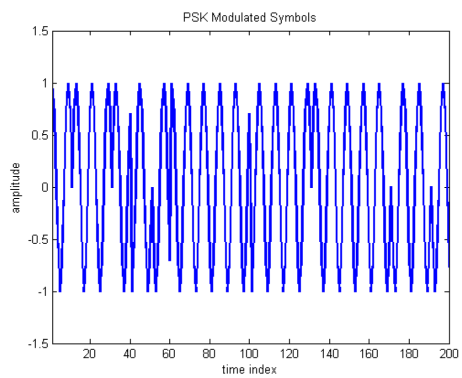


Figure 9. Phase Shift Keying modulated symbols.

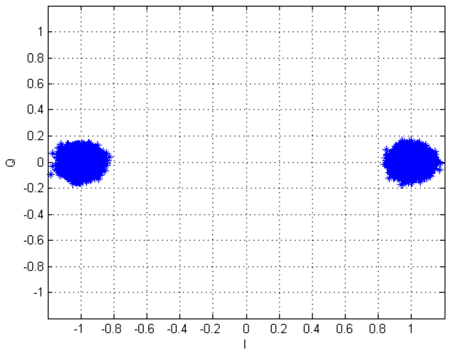


Figure 10. Phase Shift Keying constellation plot.

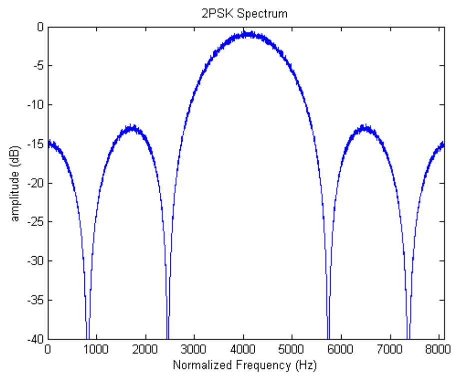


Figure 11. Phase Shift Keying spectrum.

Comparison metric for digital communication and BER curves

One of the most important metrics of performance in digital communication is the plot of bit error probability P_b versus energy per bit over noise power spectral density ($\frac{E_b}{N_0}$). This dimensionless ratio is a standard quality measure for digital communication system performance. The smaller the $\frac{E_b}{N_0}$ required, the more efficient the detection process for a given probability of error. In digital communication systems, one discrete symbol is transmitted that may be one bit or more in a fixed signaling interval. In analog, where the information source is continuous, this discrete structure does not exist. In digital systems, a figure of merit should allow us to compare one system with another at a bit or symbol level; hence $\frac{E_b}{N_0}$ renders itself naturally for that purpose. A relationship between the SNR, data rate and bandwidth is expressed in Equation 8:

$$\frac{E_b}{N_0} = \frac{S}{N}\left(\frac{B}{R}\right)$$

Figures 12 through 14 show typical P_b vs. $\frac{E_b}{N_0}$ curves for orthogonal and multiphase signaling.

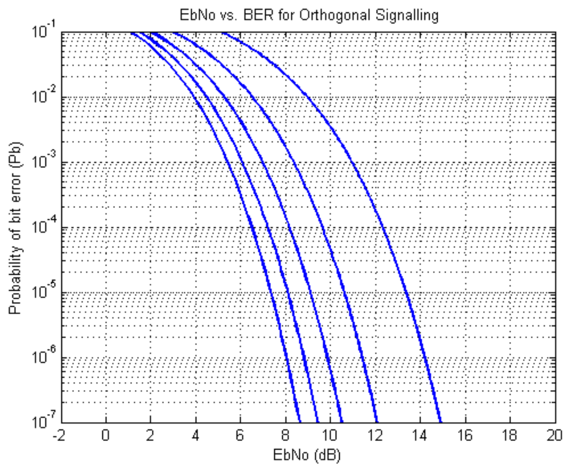


Figure 12. The curve to the left in the above chart represents M = 32 while the curve to the right represents M = 2.

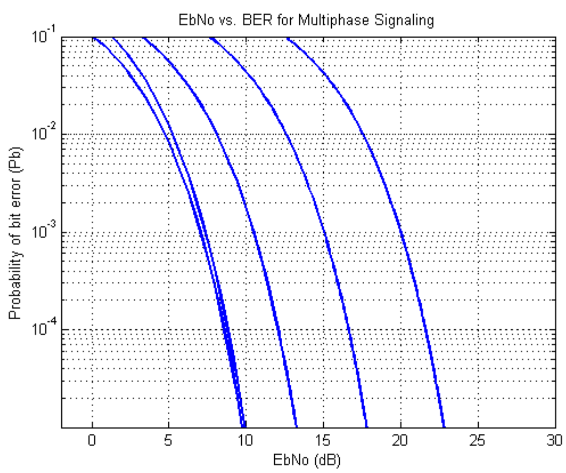


Figure 13. The curve to the left in the above chart represents M = 2 and the curve to the right represents M = 32.

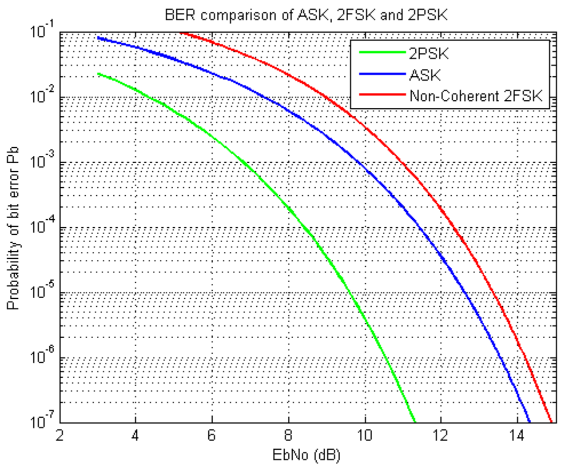


Figure 14. BER comparisons of ASK, 2FSK and 2PSK

Digital modulation methods can be classified in two ways, with opposite behavioral characteristics. The first class is orthogonal signaling; its error performance follows the curves in the first figure. The second class constitutes nonorthogonal signaling is shown in the second figure. Error performance improvement or degradation depends on signaling category.

Channel capacity

Claude Shannon's fundamental theorem states that it is possible (in principle, using some coding scheme) to transmit information with an arbitrarily small probability of error, provided that the data rate R is less than or equal to the channel capacity C . Shannon's work showed that SNR and bandwidth set a limit on transmission rate but not on probability of error. The channel capacity of a white bandlimited Gaussian noise channel is expressed in Equation 9:

$$\mathrm{C} = \mathrm{B}\log_{2}\left(1+ \frac{E_b}{N_0}\frac{B}{R}\right) \text{ bits/sec/Hz}$$

Where:

B = the channel bandwidth

$\frac{E_b}{N_0}$ = the energy/bit with an example SNR of 30 dB

Using Equations 8 and 9, the capacity of a circuit with 2.4-kHz bandwidth is approximately 24 kbps, whereas at 10-dB SNR the capacity drops to about 8.3 kbps. Thus, Shannon's theorem allows designers to apply trade-offs in bandwidth, signal power and various modulation methods to establish a communication link with a desired probability of error.

Similarly, the required $\frac{E_b}{N_0}$ for a modem operating at a channel capacity of 28.8 kbps in an AWGN bandwidth of 3.4 kHz will be approximately 16.3 dB.

Bandwidth and power constraints

The design of a digital communication system begins with the channel description, received power, available bandwidth, noise statistics, and definition of system requirements such as data rate and error performance. Two primary communication criteria are the received power and available bandwidth. In bandwidth-limited systems, spectrally efficient schemes can save bandwidth at the expense of power. In power-limited systems, power-efficient schemes can be used at expense of bandwidth.

For any digital communication system, the relationship between received power to noise-power spectral density $\frac{P_r}{N_0}$ and received $\frac{E_b}{N_0}$ is given by Equation 10:

$$\frac{P_r}{N_0} = \frac{E_b}{N_0} R$$

Where $N_0 = \frac{N}{B}$. This relationship is frequently used in designing and evaluating digital communication systems.

Bandwidth-limited systems

Bandwidth efficiency increases as BT_b product decreases. Therefore, signals with small BT_b products are employed in bandwidth-limited systems. In uncoded systems, the objective is to maximize the information rate within the allowable bandwidth at the expense of $\frac{E_b}{N_0}$ while

maintaining a required P_b . MPSK and MQAM are examples of bandwidth-efficient modulation schemes with bandwidth efficiency (Equation 11):

$$\frac{R}{B} = \log_2(\mathrm{M})\ \text{bits/sec/Hz}$$

Suppose you have to choose between MFSK and MPSK for the following parameters: bandwidth = 4 kHz, data rate = 10 kbps and $\frac{P_r}{N_0}$ = 60 dB-Hz. First you find that the received $\frac{E_b}{N_0}$ = 55 – 10*log10(10000) = 15 dB. Since the required data rate exceeds the bandwidth required, the best choice is MPSK. Next, decide on the value of M that will give a symbol rate closest to the bandwidth of 4 kHz. From M = 8, you know that the symbol rate is 3.2 kHz. Next, you'll see that for P_b of less than 10e-5, the required bandwidth is around 13 (from BER curves) which is less than the received, so the best choice is 8PSK.

Power-limited systems

For this type of system, where power is limited but bandwidth is abundant, the following trade-offs are possible:

1. Improved P_b at the expense of bandwidth for fixed $\frac{E_b}{N_0}$.

2. Reduction in $\frac{E_b}{N_0}$ at the expense of bandwidth for fixed P_b .

MFSK is an orthogonal signaling technique used in power-limited systems. It has a bandwidth efficiency of noncoherent MFSK given by Equation 12:

$$\frac{R}{B} = \frac{\log_2(\mathrm{M})}{M}\ \text{bits/sec/Hz}$$

Suppose you have an available bandwidth of 45 kHz and $\frac{P_r}{N_0}$ = 50 dB-Hz. Again the goal is to choose a modulation scheme to meet the same BER performance. The received $\frac{E_b}{N_0}$ = 50 – 10log(10000) = 10 dB. Since you have plenty of bandwidth compared to the data rate, the best modulation scheme would be MFSK. In an effort to conserve power, you should look for the largest M such that the minimum bandwidth for MFSK doesn’t

exceed 45 kHz. For M = 16, the required $\frac{E_b}{N_0}$ to keep P_b less than 10e-5 is around 8 dB (from BER curves), which is below 8.2 dB.

References

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2. Molisch, Andreas F. Wireless Communications. John Wiley and Sons, 2010. http://books.google.com/books/about/Wireless_Communications.html?id=vASyH5-jfMYC

3. Johnson, C. Richard, and Sethares, William A. Telecommunication Breakdown: Concepts of Communication Transmitted Via Software-Defined Radio. Prentice Hall, 2004.

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Consumer and Computer Interface Circuits
This module discusses the input and output circuits available from Texas Instruments for use in consumer and computer applications. It is part of a collection of modules introducing all of TI's components to seniors starting their senior project.

Technical background

As media content increasingly becomes a part of our daily lives, the need to transfer that content between devices with ease, speed and reliability is spurring development of many types of interfaces.

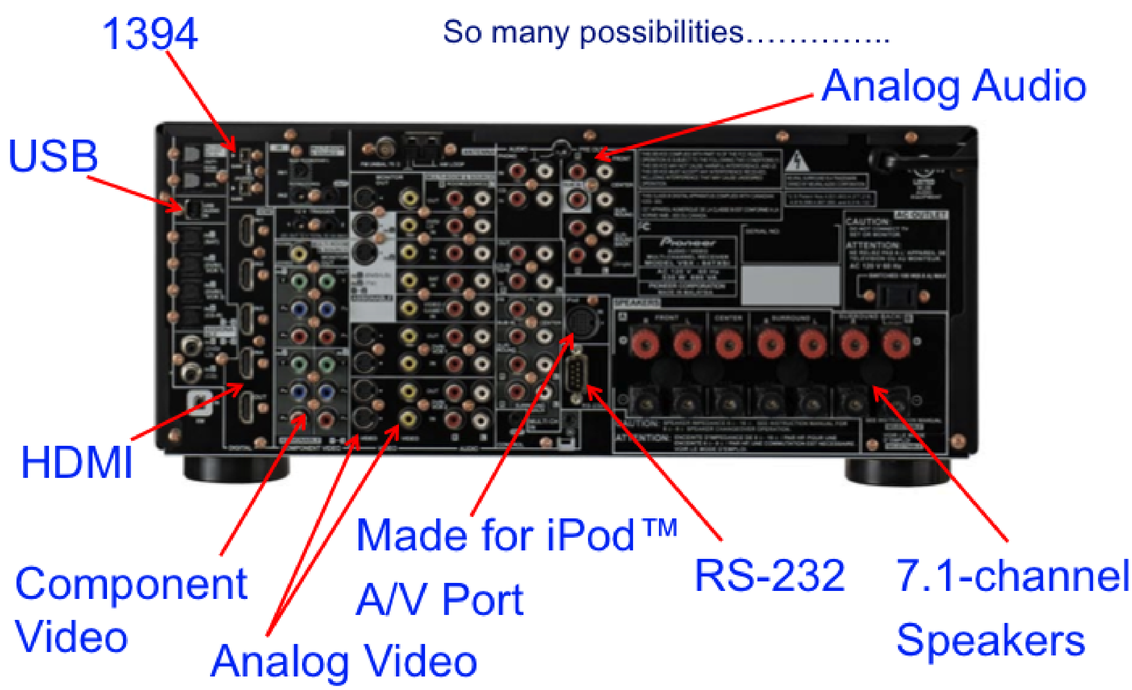


Figure 1, which shows the back panel of an A/V receiver from Pioneer Electronics, is an extreme example of a large number of interfaces on a single consumer electronic device. Having this many interfaces increases design complexity and device cost.

Electronics manufacturers face challenges in deciding what interfaces to implement on their devices to meet demanding consumer market requirements. This is becoming more challenging, as the space where you can put an interface connector shrinks with the size of the device. With the pervasiveness of high-quality digital formats, interfaces have transitioned

from analog to digital. And given the need to reduce the size of the connector, the number of wires, power consumption and interface cost, digital interfaces are also moving from parallel data transmission to serial. To maintain the data bandwidth with fewer data lines, the data rate on serial interfaces is much higher than parallel interfaces.

Some of the factors that go into selecting an interface include:

- Analog or digital.
- Ease of use, plug-and-play (robust, interoperable).
- Meeting application needs (bulk transfer vs. streaming).
- Backward compatibility (USB 3.0, 2.0, 1.1).
- Upgrade path.
- Bandwidth-supported.
- Proprietary vs. industrial standards.
- Low silicon chip cost as well as system implementation cost.
- Power consumption.
- Mechanical connector dimensions.
- Regulatory compliance (electromagnetic interference).
- Firmware and software requirements.
- Royalty fees.

HDMI™
HIGH-DEFINITION MULTIMEDIA INTERFACE

Without HDMI
DVD Player, Set-top box, &
AV Receiver

With HDMI
Equivalent functions
Higher performance

Figure 2 is an example of a digital interface replacing an analog interface, while providing ease of use and a higher-quality A/V experience.

Consumer and computing interface trends

Some of the current consumer and computing interface trends include:

- Analog interface to digital interface.
- Parallel interface to serial interface.
- Interface speed increasing (currently 10 Gbps).
- Lower power consumption.
- Lower implementation cost.
- Smaller connectors.
- Universal interface that aggregates multiple interfaces (e.g. Thunderbolt).

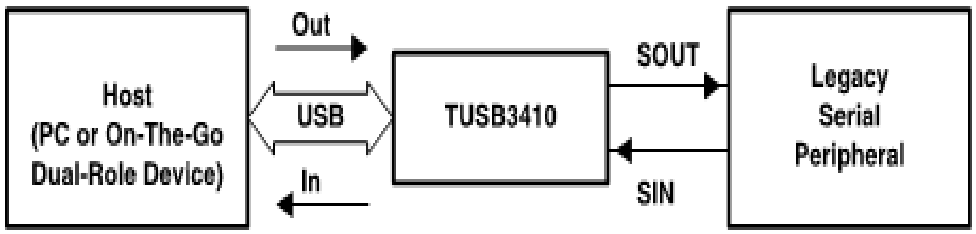
Device types

Many types of devices with different functions will help you implement the right interface on a system targeted for consumer and computing

applications. Let's take a look at a few of them.

Bridge devices

These devices bridge, or translate, between two different interfaces. TI's TUSB3410 is an example of a bridge device that provides bridging between a USB port and an enhanced UART serial port.



There are many examples of TSUB3410 bridging functions at http://www.ti.com/product/tusb3410. Figure 3 is a block diagram showing how the TUSB3410 helps designers convert a peripheral device with a legacy serial interface to a USB-compliant device.

Examples include:

XIO2001 – PCIe to PCI bridge: http://www.ti.com/product/xio2001.

TUSB9261 – USB 3.0 to SATA bridge: http://www.ti.com/product/tusb9261.

Host or device controller devices

These types of controller devices provide more functionality than bridging devices and allow designers to implement a complete interface on either a host PC device or a peripheral device.

Examples include:

TUSB7320 – USB 3.0 xHCI host controller: http://www.ti.com/product/tusb7320.

XIO2213B – 1394b OHCI host controller: http://www.ti.com/product/xio2213b.

TUSB3210 – USB GPIO device controller: http://www.ti.com/product/tusb3210.

PCI1510 – PCI cardbus controller: http://www.ti.com/product/pci1510.

Parallel to serial interface and serial to parallel interface converters

This type of device converts a parallel interface (normally single-ended CMOS) to a serial interface (normally a differential low-voltage signal) and vice versa. These devices help designers quickly transition a system using a legacy parallel interface to a newer serial interface.

Here are several examples:

SN75LVDS83C – 28 parallel in, four serial out FlatLink™ transmitter: http://www.ti.com/product/sn75lvds83c.

SN75LVDS86A – three serial in, 21 parallel out FlatLink™ receiver: http://www.ti.com/product/sn75lvds86a.

TFP410 – 24 parallel in, three serial out PanelBus DVI transmitter: http://www.ti.com/product/tfp410.

TFP401A – three serial in, 48 parallel out PanelBus DVI receiver: http://www.ti.com/product/tfp401a.

SN65LVDS301 – 27 parallel in, three serial out FlatLink3G transmitter: http://www.ti.com/product/sn65lvds301.

SN65LVDS302 – three serial in, 27 parallel out FlatLink3G receiver: http://www.ti.com/product/sn65lvds302.

Voltage-level translators

Level translator devices provide a way for system designers to convert electrical signals from one interface standard to another.

Examples include:

SN75DP139 – dual-mode DisplayPort to DVI/HDMI level translator (3.4 Gbps): http://www.ti.com/product/sn75dp139.

SN75DP129 – dual-mode DisplayPort to DVI/HDMI level translator (2.5 Gbps): http://www.ti.com/product/sn75dp129.

Switching or muxing devices

These types of devices allow multiple input sources to switch in or switch out to multiple output devices. Two types of switching devices – active and passive switches – allow designers to select the appropriate device based on cost-constraint and performance requirements.

Active switch examples include:

SN75DP126 – one input to two output DisplayPort switch: http://www.ti.com/product/sn75dp126.

TMDS442 – four input to two output DVI/HDMI switch: http://www.ti.com/product/tmds442.

TMDS361B – three input to one output DVI/HDMI switch: http://www.ti.com/product/tmds442.

Passive switch examples include:

HD3SS212 – 5.4-Gbps DisplayPort 1.2 two input to one output switch: http://www.ti.com/product/hd3ss212.

HD3SS3412 – 12-Gbps PCIe Gen III/USB 3/DisplayPort four-channel 2:1 switch: http://www.ti.com/product/hd3ss3412.

Hub or fanout devices

These types of devices allow system designers to increase the number of interface ports for a particular interface standard in a cost-efficient way without suffering performance degradation.

Examples include:

TUSB8040A – one upstream to four downstream USB 3.0 SuperSpeed hub: http://www.ti.com/product/tusb8040a.

TUSB2046B – One upstream to four downstream USB FullSpeed hub: http://www.ti.com/product/tusb2046b.

XIO3130 – one upstream to three downstream PCI Express x1 switch: http://www.ti.com/product/xio3130.

Signal-conditioning devices

These types of devices allow system designers to compensate for signal loss caused by long traces or cable length and improve signal quality at the connector or receiving device end to meet specification requirements.

Examples include:

SN65LVPE502A – dual-channel USB 3.0 redriver/equalizer: http://www.ti.com/product/sn65lvpe502a.

SN75DP130 – DisplayPort redriver with link training: http://www.ti.com/product/sn75dp130.

For a more comprehensive list of interface devices that TI offers, see http://www.ti.com/lsds/ti/analog/interface.page.

Industrial standards defining digital interfaces

There are overwhelming advantages to implement an industrial standard rather than a proprietary interface to ensure wide adoption, economy of scale for low cost, interoperability and robustness, and consumer awareness.

End-equipment application	Industrial standard digital interface
Storage (external)	eSATA,USB, 1394, PCI Express
Storage (internal)	SATA, SAS
Video (external)	DVI, HDMI, DisplayPort, 1394, USB
System bus	PCI, PCI Express
Peripheral	USB, 1394
Aggregator	Thunderbolt

Industry standards for digital interfaces

How to read a data sheet

Features. This section generally describes the type of industrial standard supported, data rate, number of channels, number of pins and package type.

Functional description or theory of operations. This section describes the function of the device in more detail and includes block diagrams, a typical application circuit, timing diagrams and register tables (where applicable).

Terminal description. This section lists the device pin terminal list, with descriptions of what the pin does.

Electrical characteristics. This section specifies the electrical signal levels of each pin as well as the power-supply requirements.

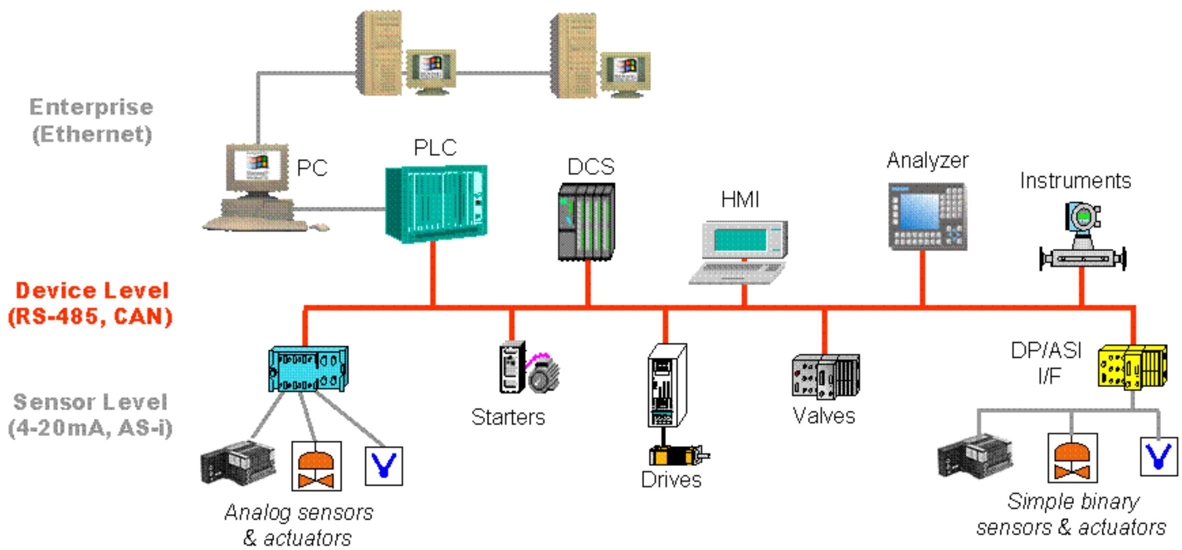
Package mechanicals. This section specifies the mechanical dimensions of the device package to help designers lay out the printed circuit board.

Industrial Interface Transceivers
This module gives a brief overview of the positioning of industrial interface (IIF) transceivers within the signal chain, their functional principles, and how to read the data sheet in order to find the right transceiver for your application. This module is one of many in a textbook designed for seniors considering the use of TI products in their senior project.

Transceiver positioning within the network hierarchy

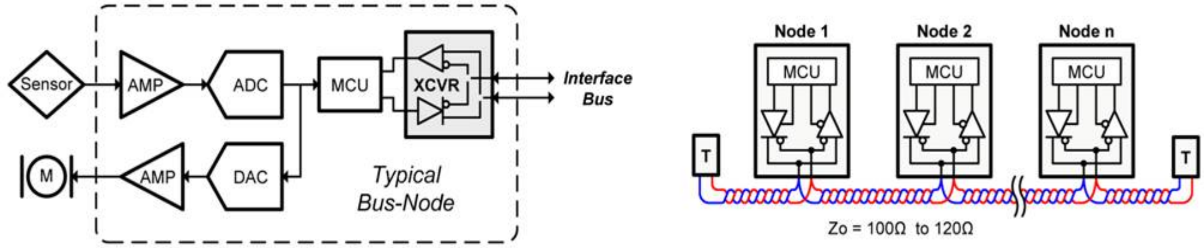
Industrial interface (IIF) transceivers operate on the device level within the industrial network hierarchy. Here, they transmit and receive digital data between network nodes that build the input/output for programmable logic controllers (PLCs), distributed control systems (DCSs), human-machine interfaces (HMIs), motor drives, valves, process analyzers and other instruments.

Figure 1 shows the positioning of IIF transceivers within the industrial network hierarchy.



In the case of a sensor/actuator interface node (the left half of Figure 2, for example), analog sensor data is conditioned by the amplifier and converted into a synchronous, digital data stream by an analog-to-digital converter, then further processed by a microcontroller. The UART interface of the MCU commonly feeds the driver with asynchronous data that is transmitted across a differential bus toward the destination node. In the opposite

direction, a network node receiving asynchronous data needs to convert this data into a synchronous stream, which upon conversion by a digital-to-analog converter provides an analog output signal to drive a motor.



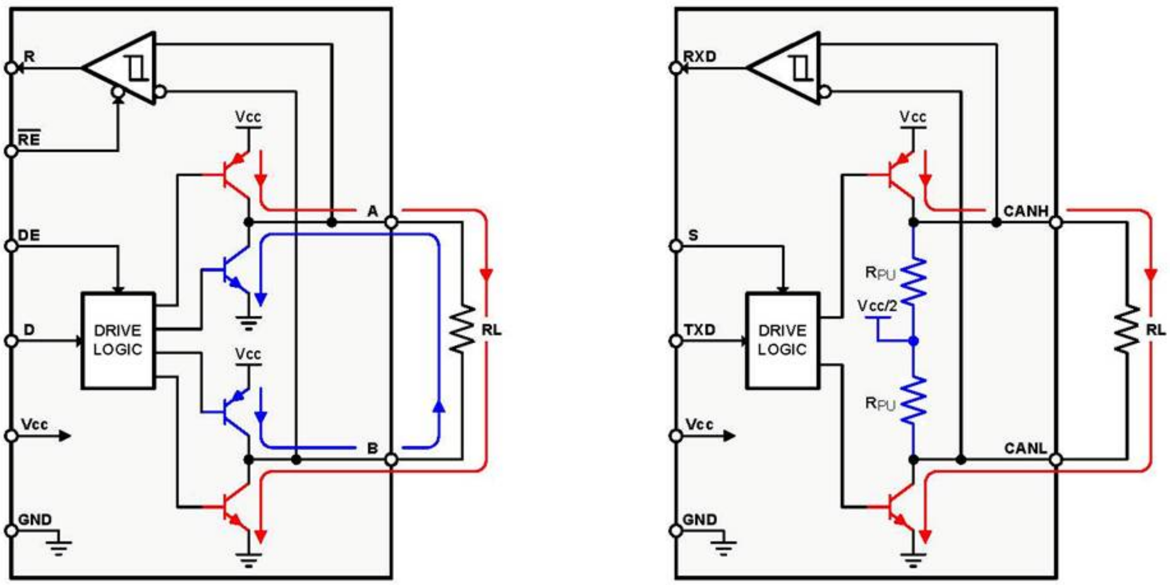
The lion's share of network designs favor a half-duplex topology: bus nodes connected in a daisy chain using unshielded twisted pair (UTP) cable with a characteristic impedance of Z_0 = 100 Ω to 120 Ω (the right half of Figure 2). Because signal propagation along the bus is significantly longer than a driver's rise and fall times, the bus cable is treated as a transmission line, thus requiring termination resistors at both cable ends whose values must match the characteristic cable impedance, $R_T = Z_0$.

Functional principles

The most popular interface standard in industrial automation and process control applications is EIA/TIA-485, better known as RS-485. Another emerging standard is the controller area network (CAN) standard, initially developed for automotive applications only.

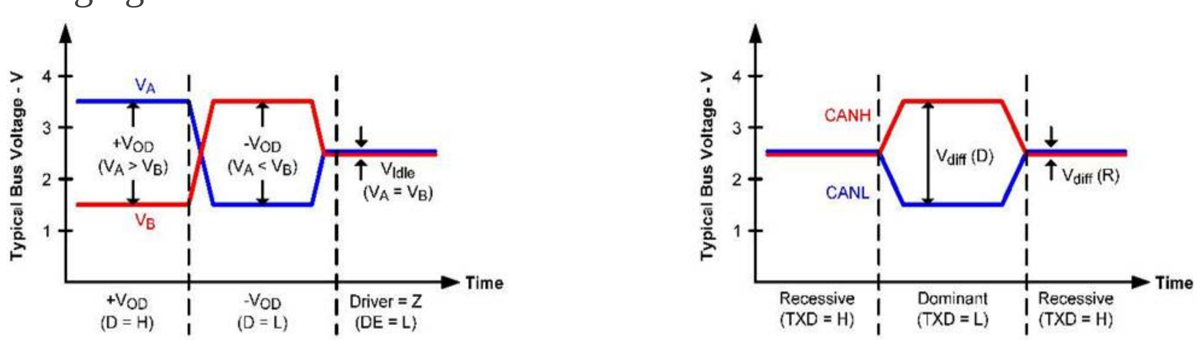
For decades, RS-485 has been – and still is – the industry's workhorse. The reasons for this lie in the robust output capability of the driver and the high noise immunity of the receiver. The output stage of an RS-485 transceiver (Figure 3, left) consists of two push-pull stages driving a bridge-tied load, R_L. R_L constitutes the sum of the termination resistors and the differential input impedance of the bus receivers. The resulting output (Figure 4, left) is a true differential bus signal with a specified minimum of V_{OD} = ±1.5 V across a maximum load of R_L = 54 Ω.

One drawback of RS-485 is that it does not allow multiple drivers to access the bus at the same time. Therefore, in order to prevent bus contention, communication between bus nodes requires a data frame to include start and stop bits, as well as address information for individual nodes.



CAN transceivers, however, possess some kind of differential open-drain structure (Figure 3, right). Here, a logic low at the driver input causes one output to swing toward the positive rail, while the other output goes negative. In this state, known as the dominant state, the bus is actively driven. The opposite or recessive state is caused by a logic high at the driver input. In this case, both output transistors are high impedance. Internal pullup resistors pull both bus lines toward $V_{CC}/2$ potential (Figure 4, right).

The benefit of this signaling technique is that it supports bus arbitration when multiple nodes attempt to access the bus at the same time – without damaging the transceivers.



General product offerings

RS-485 transceivers span a wide range of data rates, from as low as 100 kbps up to 25 Mbps. They also come with various options for half- and full-duplex topology, supply voltage, common-mode input range, ESD immunity, and isolated or nonisolated designs. Standard transceivers provide a common-mode voltage range from -7 V to +12 V in order to allow for a ground potential difference (GPD) between a driver and a remote receiver of up to ± 7 V. GPDs as high as 20 V use stronger transceivers with common-mode voltages from -20 V up to +25 V. For even higher GPDs of several hundreds of volts, typically found in harsh industrial environments, use isolated transceivers. These devices come with integrated galvanic signal isolation between the control and the bus signals.

CAN transceivers do not offer this wide a parametric choice, but do offer a variety of functional features instead. These include slope control, auto-baud, bus wakeup, loop-back mode, isolated or nonisolated, and other functions.

Finding the right CAN transceiver

Finding the right CAN transceiver is easy if you simply follow these recommendations.

For 5-V applications, choose the SN65HVD255, SN65HVD256 or SN65HVD257, as they represent brand-new transceiver designs for standard and high-speed CAN applications. All three devices are specified in one data sheet: http://www.ti.com/general/docs/lit/getliterature.tsp?genericPartNumber=sn65hvd255&fileType=pdf .

For 3-V applications, choose a device from the SN65HVD23x family. These devices come with various features; some of them include slope control for low EMI applications. You can parametrically search for all 3-V CAN transceivers here: http://www.ti.com/paramsearch/docs/parametricsearch.tsp?family=analog&familyId=540&uiTemplateId=NODE_STRY_PGE_T .

For large GPD or to prevent ground loops, use the ISO1050: http://www.ti.com/general/docs/lit/getliterature.tsp?genericPartNumber=iso1050&fileType=pdf .

Finding the right RS-485 transceiver

Finding the right RS-485 transceiver is a little more complex because of the wider range of parameters from which to choose. Your first mandate should be to get your data link working reliably within the environment for which it is intended, which means **not just in the lab**. With this in mind, options for supply voltage, packaging and even ESD immunity become secondary choices, as they represent parameters you can adapt your circuit to. For example, controlling a 5-V transceiver with a 3-V MCU requires either a 3-V to 5-V charge pump or a 5-V to 3-V LDO. Or, if your transceiver has low ESD immunity, use an SM712 transient suppressor in front of it at the board connector.

You should typically start your project by determining how many bus nodes you need to connect to and across what distance the data link has to run before looking at a data sheet. Once you've got a rough idea, the most important parameters to look for are temperature range, data rate or driver rise and fall time, unit load or number of nodes, common-mode voltage range, supply current, and fault protection.

Temperature range

The wide range of applications for RS-485 transceivers has led to a number of different temperature ranges. Before evaluating data sheet parameters, make sure you have selected the correct temperature range for your application requirements. The specified operating temperature range is almost always given at the end of the device description on the front page of a data sheet.

Unit loads or number of nodes

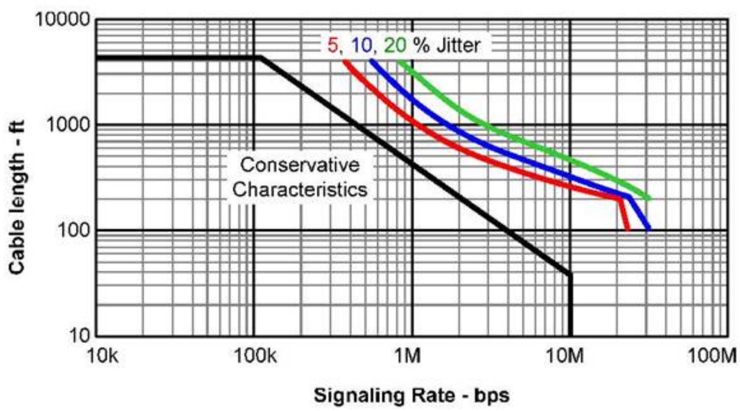
For each bus line, RS-485 defines a unit load (1UL) as a 12-kΩ common-mode resistance between one of the bus lines and ground. The standard also specifies that a driver must be able to drive a total of 32 unit loads or 375 Ω

on the bus. Thus, a transceiver with a 1/8 unit load has 8 times the input impedance of a unit load, which is 8 x 12 kΩ = 96 kΩ. Dividing 96 kΩ by 375 Ω yields 256, which is the maximum number of transceivers connected to the bus.

You can usually find either the unit load value or the maximum number of nodes listed on the front page of the data sheet. If not, turn to the receiver section of the data sheet and look for the specified common-mode input resistance. Divide this value by 375 to find your maximum number of transceivers.

Data rate or driver rise and fall time

As shown in Figure 5, you can determine your maximum data rate for a given bus length, or vice versa – a maximum bus length for a given data rate. The longer the cable length, the lower the data rate. Long-distance networks (1,000 feet to 4,000 feet) such as e-metering applications often use data rates of 10 kbps to 250 kbps. Low data rates also allow for longer stubs, the distance between the cable trunk and the actual transceiver terminals on the board. The maximum data rate is usually given on a data sheet's front page. If not, turn to the Driver Switching Characteristics section and find the maximum driver rise time, tr. Then calculate the maximum data rate: DR = 0.3 / tr.



Common-mode voltage range

A transceiver’s common-mode voltage range is usually listed in the Recommended Operating Conditions table as "voltage at any bus terminal

(separately or common mode), VI." As mentioned earlier, standard-compliant transceivers provide a range of -7 V to +12 V. High common-mode transceivers allow for -20 V to +25 V. For higher common-mode requirements, choose isolated RS-485 transceivers.

Supply current

The supply or quiescent current is specified under no-load conditions for various driver/receiver on/off configurations. The most important configuration, however, is when the driver is disabled while the receiver is enabled, as this represents the main operating mode during a transceiver's lifetime. A low-power transceiver such as the SN65HVD3082 consumes only 600 μA in this condition, while a robust transceiver with 70-V standoff like the SN65HVD1785 requires a full 4 mA. The supply-current specification is commonly specified under Electrical Characteristics.

Fault protection voltage

This is a standoff voltage that allows your transceiver to survive should a broken bus cable come in contact with adjacent power cabling or other high-voltage contacts. This voltage is listed under Absolute Maximum Ratings as "voltage range at bus pins."

You can parametrically search TI's RS-485 transceivers here: http://www.ti.com/paramsearch/docs/parametricsearch.tsp?family=analog&familyId=545&uiTemplateId=NODE_STRY_PGE_T .

System Components
This module discusses the system components at TI and helps seniors find the right system components for their senior project.

System components

The term “system components” covers a broad universe of semiconductor devices, ranging from the simply functional to the extremely complex. Given the variety in this class of components, there is one common denominator in that all of them provide solutions to specific problems. In this chapter, we will provide examples of three categories of components: integrated solutions, line drivers and basic functions.

In previous chapters, you learned how to use the device data sheet to evaluate performance and use conditions, so we will not provide a detailed technical discussion here.

Integrated solutions

Figure 1's depiction of a general system block diagram could probably represent your senior project as well. Previous chapters have described how to evaluate devices that make up such a general system: op amps for the creation of filters, control systems or input and output signal-conditioning systems, microcontrollers or DSPs that process data captured by the system, power-management solutions, wireless solutions, and interface options. [missing_resource: Signal chain block diagram.jpg]

By necessity, most of the information in this book is based on basic circuit elements – an op amp, a low-dropout (LDO) regulator or a specific microcontroller – that represent the system building block under discussion. But what about real-world applications, which hopefully your senior projects are tackling? Since the invention of the integrated circuit by Jack Kilby in 1958, the semiconductor industry has continually integrated more and more into its products. From Bell Lab’s single transistor to Kilby’s integrated circuit, from Texas Instruments' single-chip DSP to today’s embedded system engines (powering smartphones, automobiles, washing machines and practically everything else), the inexorable technological march to more complex integrated solutions continues.

You might be asking yourself, “Why shouldn’t my senior project benefit from more complex solutions?” The question can also be reworded as, “What if I took advantage of application-specific solutions used by industry design teams?” The answer to both questions is that it depends. It depends on the application you are addressing and the maturity of the solution you are looking for. If a device you are interested in provides available samples on its www.ti.com page, the technology is mature enough for your senior project.

It also depends on your team’s ability to understand and manage the functionality so that it can be used properly in your system. You should also consider the trade-offs in time and effort to use an integrated solution. A simple example would be in power management. The "Power" chapter in this book introduces the various components for power management separately, yet the application of these elements to a real-world application can be complex.

Consider the challenge of creating a lithium-ion battery charger for your project. The physics of the Li-ion battery charging under load are complex and require a detailed solution. While the creation of such a charger would have once been a suitable senior project, the bq24040 is a single-input, single-cell Li-ion battery charger that provides the solution in a single device. The bq24040 charges the battery while it is powering a system load. The battery is charged in three phases: conditioning, constant current and constant voltage. Clearly, this is a sophisticated solution, which when used in your project frees team resources to address other basic elements.

If you decide to choose the bq24040, you must make sure that the basic parametric and functional attributes of the device meet your system's needs. As described in previous chapters, a close inspection of the data sheet is a requirement for successful implementation. If you find yourself with a challenge you cannot address, then take advantage of the application notes associated with the device, or use the E2E Community, http://e2e.ti.com.

To explore the use of system components further, let's consider a more complex device. The ADS1294 family incorporates all of the features commonly required in medical electrocardiogram (ECG) and electroencephalogram (EEG) applications. The ADS1294 family of analog

front-ends (AFEs) provides multichannel, simultaneous sampling; 24-bit, delta-sigma (ΔΣ) analog-to-digital converters (ADCs) with built-in programmable gain amplifiers (PGAs); internal reference; and an onboard oscillator. Figure 2 is a block diagram of this device.
[missing_resource: ADS1298 block diagram.jpg]

Reviewing the data sheet for this family of devices shows a complex solution to a sophisticated application. With devices as complex as the ADS1298, an in-depth exploration of the data sheet exceeds the scope of this chapter. However, the concepts previously described are applicable to the specific functions on the device.

If you decide to use an application such as the ADS1298, you will be designing the rest of your system to match the input and output characteristics – functional and parametric – of the ADS1298. When using a device as complex as the ADS1294, you must pay special attention to the timing relationships of the various signals; failure to do so will result in a bad outcome. Again, if you find yourself with a challenge you cannot address, take advantage of the application notes associated with the device or use the E2E Community, http://e2e.ti.com.

As the bq24040 and ADS1298 devices illustrate, integrated system components incorporate a plethora of functional solutions. These solutions cover all aspects of devices that have been discussed in previous chapters of this book, such as processors developed to support applications like motor control, battery-management systems with embedded controllers, touch-screen controllers, and many more.

Line drivers

At some point, you will be faced with a project that requires transmitting data across a several-inch-long backplane on a printed circuit board, or perhaps uses a cable that's several feet long. Electrically, you should think of the backplane or cable as transmission lines. Pay careful attention, because lack of signal integrity can result due to mismatched impedances.

In the bus interface environment, signal integrity is simply maintaining the characteristics of the input signal at the receiving end of the bus, where the

bus is represented as a distributed RLC network. The impedance of the line driver, the bus network and the load on the bus can interact with each other to create signal distortions caused by energy reflections. The mathematics of these interactions are complex but can be simplified by modeling the system, as shown in Figure 3, and its associated reflection coefficient, shown in Equations 1(a) and 1(b).
[missing_resource: Transmission line block diagram.jpg]

$$\mathrm{R(Source)} = \frac{\mathrm{Z(S)\text{ - }Z(t)}}{\mathrm{Z(S) + Z(t)}} \quad (1a)$$

$$\mathrm{R(Load)} = \frac{\mathrm{Z(L)\text{ - }Z(t)}}{\mathrm{Z(L) + Z(t)}} \quad (1b)$$

Where:

R(Source) = the reflection coefficient at the source

R(Load) = the reflection coefficient at the load

Z(S) = impedance of the source

Z(L)= impedance of the load

Z(t) = impedance of the transmission line

Inspection of the reflection coefficients shows that if the impedance of the source driving the transmission line is matched with the impedance of the transmission line itself, there is no reflection. The same holds true for the load. Similarly, if the impedances are not matched, you can expect reflections to occur, resulting in distortions of the signal being propagated on the transmission line.

Signal characteristics such as the rise and fall time (slew rate) of the signal can also impact the integrity of the signal being transmitted. Slew-rate limitation also limits the data transmission rate of a given bus configuration. Therefore, bus interface products are designed to optimize not only bus impedance matching but signal slew rate as well.

In practice, perfect matching is difficult to achieve because of the trade-offs between drive currents, output voltages and frequencies. You can optimize the performance of the bus and minimize the impact of these distortions by carefully selecting the line drivers or bus interface devices. For buses that follow industry standards such as LVDS, PECL and many others, devices exist that provide a robust switching solution. The "SLL Advanced Bus Interface Logic Products Selection Guide and Reference," http://www.ti.com/lit/sg/scyt126/scyt126.pdf, provides an in-depth guide to the various options available.

Finally, when dealing with buses and signal-integrity challenges, one of the best things that you can do is use an oscilloscope to observe the impact of the various options available on the actual signal. Experiment with different drivers and termination schemes to determine the best solution for your project.

Basic functions

Basic functions incorporate logic gates, multiplexers, analog switches and many other relatively simple functions. This category of devices is discussed separately from integrated solutions, primarily because basic functions tend to be relatively small circuits that perform a simple action.

Examples of these types of devices include simple logic gates (NAND, AND, OR), stand-alone registers and flip-flops, and clock drivers. Use keywords that describe the function you need in the www.ti.com search engine to view the available options.

As with all products, it's imperative that you read the data sheet to confirm that the recommended operating conditions meet your application. First, look at the supply voltage ratings and input voltage levels to ensure that the device will function in your system. Then review the output current properties to confirm that the device can drive the load you need to drive. For storage elements such as flip-flops and register files, frequency characteristics are also key design criteria.

Conclusion

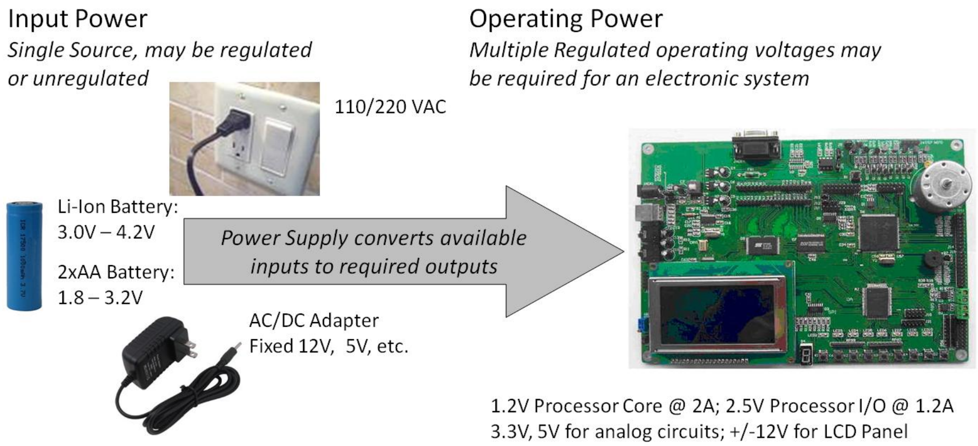
System components encompass a large variety of products. We recommend that you explore the options available to you at www.ti.com. Indeed, one of the pleasures of the engineering design process is sorting out the available solutions to meet your project's needs.

Power Management
This module gives a brief overview of the Texas Instruments power management portfolio, how to read a data sheet on power-management devices, and how to pick the right one for some sample applications. This module is one of many in a textbook designed for seniors considering the use of TI products in their senior project.

Power-supply circuitry

Many electronics textbooks often ignore the power supply. It is simply assumed that a bias rail for an amplifier circuit or the VCC operating voltage for a microprocessor is "just there." But in reality, engineers developing a complete system will need to create (or at least select) an appropriate solution to generate the necessary power-supply rails for the rest of the circuitry. The complexity of these circuits can vary considerably depending on the application.

The purpose of this chapter is not to provide a detailed explanation about the theory and design of voltage regulator circuits, but to allow you to understand how to implement a power-supply solution for a given system using readily available integrated solutions. For many DC/DC conversion applications, system design engineers can now select from a wide variety of readily available catalog solutions to implement in their power systems without becoming a power-supply design specialist. Figure 1 illustrates the power conversion circuitry in an electronic system.



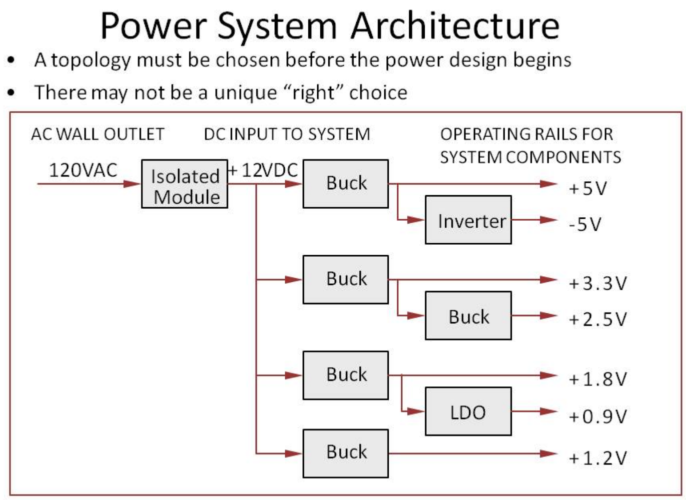
Determining the power-supply requirements and architecture

As indicated in Figure 1, the basic purpose of a power-supply circuit is to convert the voltage available from the “bulk” input power source into one or more regulated voltages as required by different subsystems/circuits in the rest of the design. For example, a typical microprocessor may require 1.8 V for the processor core, plus other voltage levels like 2.5 V or 3.3 V for peripherals or I/O devices. If the system has a display, you will need additional higher-voltage rails to bias and/or illuminate that display.

Let's outline one approach to the process of developing a power system for a given application (see Figure 2 as well):

- What type of input source is available?
    - Understand how much bulk (raw) power you have available, and if it is sufficient to operate all of the circuitry in the overall system.
- Determine the power budget:
    - Understand the basic needs for the output power rails required – the volts and amps required for each part of the system to operate.
- Consider the accuracy (regulation) requirements for each power output rail:
    - Understand ripple and noise requirements for each power rail.
    - If high efficiency is required, consider switch-mode converters where appropriate.
    - Consider linear regulators for sensitive rails such as audio or radio circuits (including linear post-regulators after a switching supply when needed), or for low-power rails where efficiency is less important.
- Consider power-sequencing requirements for a given processor or system and how the different rails will be controlled (some microprocessors require multiple power rails, and they must be turned on/off in a specific order).
- Check thermal stress/power dissipation limits.

- Choose the regulator architecture (linear or switch-mode) for each output required.
- Assemble and evaluate prototypes – use evaluation modules (EVMs) from TI, or build a dedicated power printed circuit board (PCB) customized to your system requirements.



For example, let's assume that the input power available to a system comes from an AC/DC wall adapter, with an output rating of 12 V at 1-A maximum load. (The design of high-voltage and AC/DC isolated power supply circuitry will not be discussed in this chapter.) The system in this example comprises the following major subsystems:

- A microprocessor circuit that requires 1.8 V at 1 A and 3.3 V at 500 mA.
- A display that requires a +5-V bias rail at 50 mA, and a backlight consisting of six series LEDs driven at up to 20 mA (white LEDs are in the range of 3.5 V/LED, so you can assume about 21 V for the series string to operate at full brightness).
- An audio amplifier that requires 5 V at 200 mA.

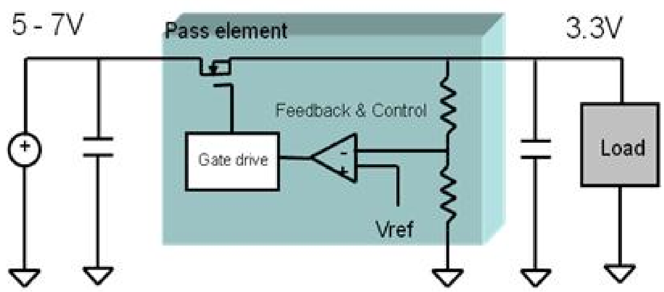
A quick estimation of the maximum system power gives you the following (Equation 1):

P_{total} = (1.8 x 1) + (3.3 x 0.5) + (5 x 0.05) + (21 x 0.02) + (5 x 0.2) W = 5.12 W (eqn 1)

Therefore, if all of the power-conversion circuitry is 100 percent efficient, it would take a little more than 5 W to operate the system at maximum load. In reality, of course, a typical power-conversion circuit will operate at less than 100 percent efficiency, but given that you have a total of 12 W available from the input power source, you should have more than enough to operate the system.

Important terminology/definitions

Linear regulator. The most basic form of voltage regulator. In this type of device (see Figure 3), a pass element (transistor) is connected between the input (power source) and output (load). The control circuit operates the pass device in its linear range to maintain a regulated voltage level at the output, even if the input voltage is variable.

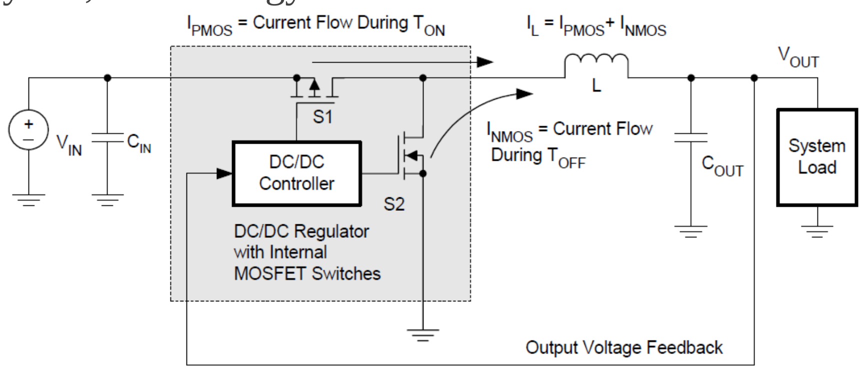


The linear regulator is simple and relatively inexpensive; however, it has some limitations. Most notably, the regulated output must always be lower than the input voltage. Furthermore, if there is significant differential between the input and output (a high input voltage such as 12 V and a regulated output such as 3.3 V, for example), there will be significant loss in this type of circuit. Any excess voltage is simply lost (dissipated) across the pass element, so this type of regulator can be very inefficient and generate significant heat at high load currents or large input/output differentials.

Low-dropout (LDO) regulator. This is a special type of linear regulator that is designed to allow operation down to a relatively low differential between the input and output voltages. Traditional linear regulators (like the LM7805) require the input to be approximately 3 V higher than the output

voltage to maintain regulation. LDOs can operate down to input voltages that are only 100-200 mV above the desired output setpoint. This type of circuit has become so popular that most integrated linear regulators are now generically referred to as LDOs.

Switch-mode power supply. A switch-mode power supply is a power-conversion circuit that operates in a completely different mode from a linear regulator. The pass element(s) are not operated in the linear (dissipative) range, but driven by a clocking (gate drive) signal to switch between fully on and off states. Instead of dissipating power across the pass elements, they operate at a controlled ratio of on to off time to transfer just the right amount of energy from the input source to generate a regulated output voltage as required by the system. The ratio of pass element on time to the total switching period is defined as the **duty cycle**. As the load conditions (and also possibly the input voltage) vary, the converter's duty cycle is adjusted by its control circuit to maintain the desired output voltage. At lower duty cycles, less energy is transferred to the output; at higher duty cycles, more energy is transferred.



The switch-mode concept has the significant advantage of being able to efficiently convert power from any input voltage to any desired output voltage. A **buck** or **step-down** converter (Figure 4) can convert a given input voltage to a lower output voltage. A **boost** or **step-up** converter can convert an input voltage into a higher output voltage. A **buck-boost** converter can generate a regulated output voltage from an input that may vary both below and above the desired output level. (For example, if using a variable input source such as a battery, the input voltage may range from 2.5 V up to 6 V depending on the battery. If a steady 5-V output is required

across the full battery range, a buck-boost design can provide the needed output.)

The trade-off for the performance advantages of the switch-mode converter is that you must follow a more complex design process; cost and complexity increase in exchange for performance and flexibility. However, many integrated catalog solutions now exist to simplify this task. A more complete explanation of the basic operation of switching converters is provided in the references.

Efficiency. Efficiency (**H**) (Equation 2) is the ratio of power delivered to the load versus power drawn from the input. For an ideal (perfect) power supply, 100 percent of the power taken from an input source is delivered to the load to perform useful work. In reality, today's high-efficiency switch-mode converters may have efficiency ratings in excess of 90 percent; however, the values may vary widely depending on operating conditions.

$\mathbf{H} = P_{output} / P_{input}$ (eqn 2)

Ripple. In switch-mode power supplies (which operate by turning pass devices on and off at a high frequency), the output voltage will have a small AC component (typically mV) superimposed on the DC. This AC component, measured as a peak-to-peak voltage, is the **ripple voltage**.

Regulation accuracy. An ideal voltage regulator will produce a fixed-output DC value that stays at the exact setpoint (such as 3.3000 VDC) under all operating conditions. In practice, the output voltage may vary slightly above and below the setpoint by some finite percentage as a result of input voltage changes, output current (load) changes, reference signal accuracy variation and temperature change. Most voltage regulator data sheets have electrical specification tables that will express output voltage accuracy either as absolute values (+/- mV) or percentage change from the nominal output setpoint value.

Transient response. Any voltage regulator circuit is, at its core, a control system. Its purpose is to maintain a stable output voltage regardless of variations in input voltage, load current or temperature. As with any control system design, there must be a balance between speed (the ability to

respond quickly to any perturbation) and stability. In most systems, when some perturbation occurs at the input, there will be a brief change in the output until the control loop has time to respond. The **load transient** response of a power supply refers to the change in output voltage as a result of a step change in the load current. The **line transient** response refers to the change in output voltage as a result of a step change in input voltage. A well-designed voltage regulator will have minimal deviation from the steady state (regulated) value of its output and quickly settle back to its desired regulation point when any type of line or load transient occurs. A badly designed power supply, on the other hand, can have significant oscillation or instability on the output due to certain types of input or load transients. The following section will show examples of these responses.

You should know several other critical terms/definitions, including **dropout**, **PSRR**, **and quiescent current**. Reference 1 provides a complete explanation of these and other important specifications/parameters associated with power supply circuits. Reference 2 and Reference 3 are comprehensive textbooks that cover most aspects of power-converter design. Some power-converter circuits have multiple modes of operation to maximize efficiency over a wide load range. The concepts of fixed- and variable-frequency operation, including pulse-width modulation (PWM) and pulse-frequency modulation (PFM), are discussed in Reference 10.

Understanding the data sheet: voltage regulator component selection

For these examples, please refer to the TPS54140A and TPS62160 data sheets, along with the text below.

Just like an op amp data sheet, a voltage regulator data sheet can also be somewhat overwhelming. Numerous parameters are listed for a device with (relatively) few pins. But as noted in the chapter on op amps, the front page will generally provide a quick summary of features and suggested applications that will indicate the typical intended uses of the device. As with other analog IC devices (like the op amp), some specific parameters may be more important than others for a given application. The typical performance graphs can also give some fundamental information about how the device will perform under different operating conditions – this information may not be guaranteed for all conditions, but it can tell you

much about the basic characteristics of the part. The electrical specifications tables will provide guaranteed maximum and minimum values of certain critical parameters, subject to the test conditions defined at the top of each table.

The applications section will offer some discussion about how to use the device, and calculation procedures for selecting external components such as inductors and capacitors. It provides tips, warnings and advice on how to best use the device. Finally, most devices will also have an evaluation module (EVM) available. Even if you do not use the EVM, you can download the EVM user guide and schematic from the product data folder at www.ti.com and get a detailed schematic, recommended external components, test procedures and PCB layout for each device.

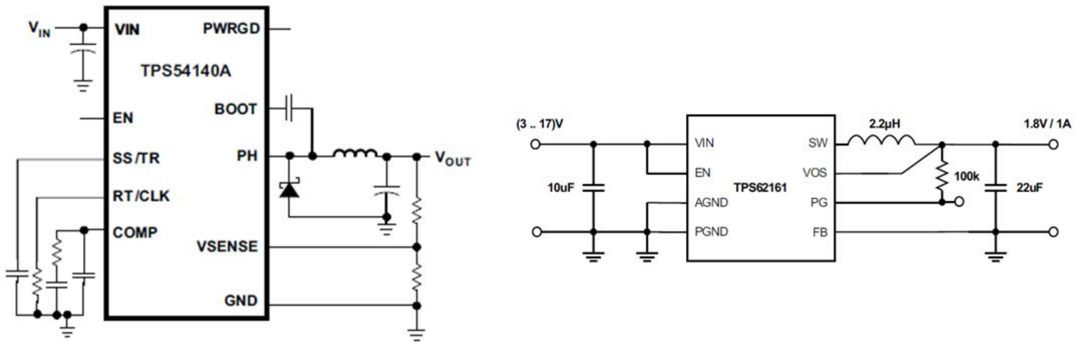
The Web-based selection tools and component landing pages on the TI website will typically provide basic information about whether a component can be used for a particular requirement. However, in many cases, there may be multiple devices that appear to satisfy the same requirement – to understand which of these devices is the best fit requires a slightly deeper understanding of the application requirements and a more complete review of the critical parameters of a device based on the component data sheet.

As an example, consider a system design requirement to generate a precisely regulated 3.3-V output from a poorly regulated 12-V input, delivering up to 1 A of output current to the load. There are many ways to solve this problem. The best way depends on the additional requirements of the application, and understanding which of the key performance parameters are most important. For example, the most efficient solution may not be the lowest cost. Or perhaps efficiency is nice to have but not as important as rugged, robust design and tolerance to high-voltage transients in a noisy environment. Or it may be necessary to find a physically very small solution to fit in a tightly constrained space for a portable product.

Let's compare two devices that, at first glance, appear to solve the same problem: the TPS54140A and TPS62160 switch-mode buck regulators. Both of these devices are perfectly capable of generating 3.3 V with +/-3 percent accuracy from a loosely regulated (12 V +/-10 percent) input voltage. However, observing some of the details of each device from the

data sheet will show that the TPS54140A may be the better choice for some types of applications, while the TPS62160 is more suited for others. First, observe the basic schematic shown on the first page of each device's data sheet, as in Figure 5.

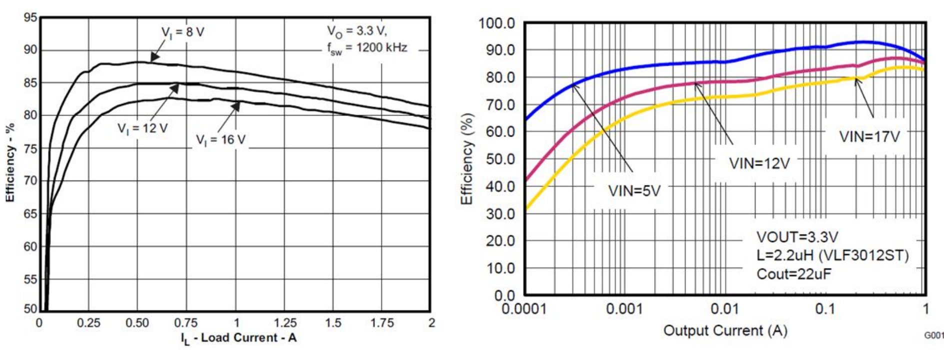
12V In → 3.3V Out @ 1A Load Current – Two Possible Solutions



TPS54140A TPS62160

From the schematic, you can immediately see that the TPS54140A has more external components associated with it. You can check the cost of the devices on the website as well, so the TPS54140A solution will likely have higher total cost and design complexity compared to the TPS62160. But because certain performance parameters can be controlled externally with the TPS54140A, you have a greater degree of flexibility to adjust operating characteristics such as the switching (clock) frequency or startup times by changing the external component values. (This is not possible with the TPS62160, which has all of these characteristics fixed internally to the silicon). Next, look at the efficiency plots in each data sheet (Figure 6).

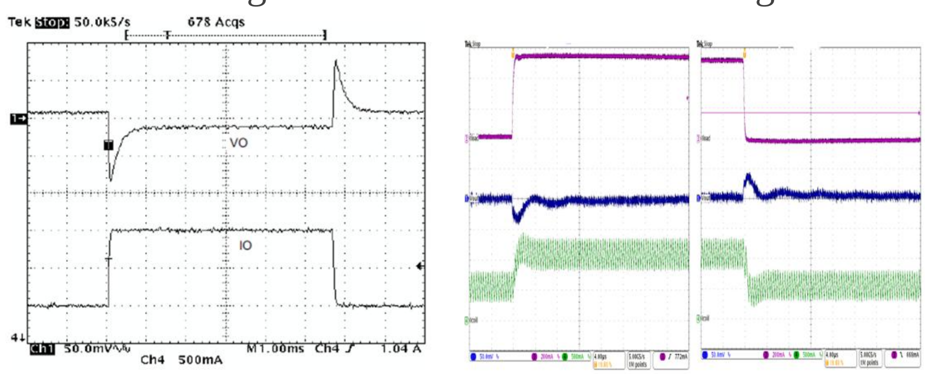
Efficiency vs. Load Current



TPS54140A TPS62160

A few differences are immediately obvious. First of all, the TPS54140A plot is shown using a linear scale for the load current axis, while the TPS62160 uses a logarithmic scale. This is because the TPS62160 is optimized to work in applications that require high efficiency over a wide range of loads, including very light loads (such as processors that may be in standby mode). The TPS54140A, on the other hand, is primarily intended to handle higher load currents (and is tolerant to much higher input voltage ranges as well). Thus, for applications that require high efficiency at very light loads, the TPS62160 will be the better choice. On the other hand, if you need a more rugged or robust solution to handle continuous high current, the TPS54140A may be a better option.

Now take a look at the transient response plots in each data sheet (see Figure 7). Not all data sheets will show test data for the exact same conditions. If you need a true apples-to-apples comparison, you can test each circuit using the EVM for each device using identical load conditions.



TPS54140A   TPS62160

Look at the two most similar plots available from the respective data sheets. The TPS54140A plot shows an output voltage response (top trace) to a 0- to 1-A load current step (bottom trace), while the TPS62160 plot shows the output voltage response (blue) and inductor current (green) for a 500-mA to 1-A load current step (purple). The horizontal scale for the TPS54140A plot on the left side is 1 mS/division. The corresponding scale for the TPS62160 plot is 4 µS/division. So, you can see that the TPS62160 has a much faster settling time (several microseconds) than the TPS54140A (nearly 1 ms) for a comparable load transient.

Table 1 summarizes some of the other key parameters for both devices.

	TPS54140A	TPS62160
1K Unit Cost	$1.60	$1.00
Operating Frequency	100 KHz – 2.5MHz, externally settable	Variable, up to 3MHz, internally controlled
Iq (Operating)	116 uA	17 uA
V_{IN} Range	3.5V – 42V	3.0 – 17V
V_{OUT} Range	0.8 – 39V	0.9 – 6.0V
I_{OUT} (MAX)	1.5A	1A
IC Package / Size	MSOP-10: 3x5mm SON-10: 3x3mm	MSOP-8: 3x5mm SON-8: 2x2mm
Number of external components	12	4

Table 1. summary of other key parameters for both devices.

Each device has strengths and weaknesses in different areas – so you will need to consider which parameters are most important for your specific use case (end application) in order to decide which device to use. If the application is battery-operated or needs the smallest possible physical space for the design, the TPS62160 would be the best choice. If on the other hand, the application requires higher load current or input voltage tolerance, choose the TPS54140A.

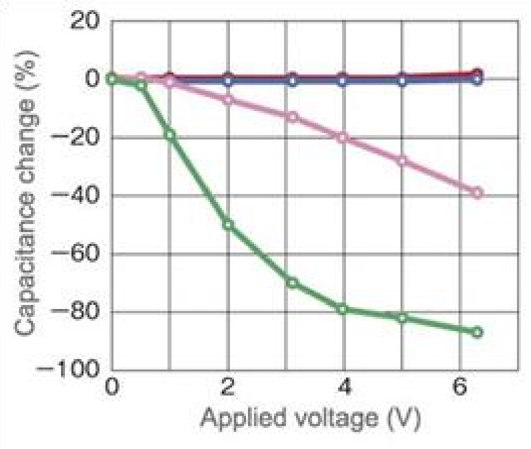
External components – inductors and capacitors

In addition to the silicon components, the proper external passive elements (resistors, capacitors and inductors) are essential to the operation of a power-supply circuit. A rudimentary understanding of the non-ideal aspects of these passive components will help you properly select the right type of external components for your design. For example, an ideal inductor has zero resistance at DC, while an ideal capacitor has zero resistance at infinitely high frequencies. Furthermore, these ideal components retain their characteristic inductance (or capacitance) across the entire frequency spectrum.

Consider, for example, that the wires used to wind around the magnetic core of an inductor are made of good but imperfect conductors (like copper) and will have a finite, nonzero DC resistance (DCR). Thicker wires will have lower DCR, but that will result in a physically larger and more expensive

component. So you will need to choose a component that optimizes low-enough DCR but still meets the cost and size requirements for a particular design.

As another example, the behavior of a real capacitor under different operating conditions is a function of its physical construction and the type of dielectric materials used in the component. The data sheets for these components should illustrate the variation in effective capacitance versus DC bias (operating voltage) (see Figure 8), as well as the chance in capacitance vs. operating frequency. See Reference 4 for a more complete discussion on external component selection procedures for power-supply circuits.



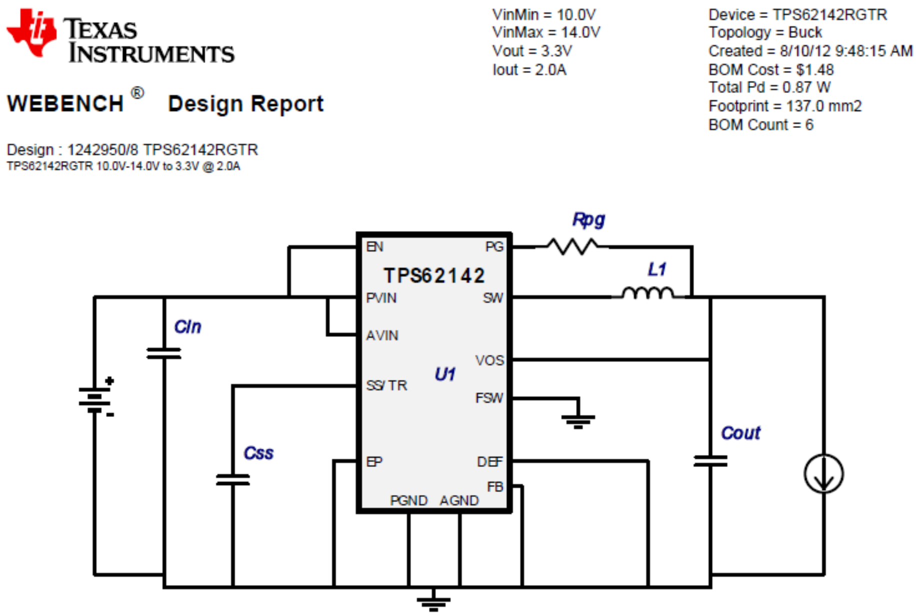
"Non-ideal" Capacitor Behavior: Change in effective capacitance vs. Applied Voltage for different types of dielectric materials

Source: Murata Corporation; www.murata.com

WEBENCH® design example

Most voltage regulator/DC/DC converter data sheets offer some amount of information on designing the overall power circuit, including example schematics and layouts. TI also provides the WEBENCH® free online power-supply design tool to assist with component selection and to provide an initial analysis of the circuit's operating conditions. You can access the WEBENCH tool, as well as other design tools, from (www.ti.com) or at webench.ti.com. Figure 9 is an example of a design schematic for a (nominal) 12-V input, 3.3-V output converter with a load-current rating of 2-A output. From the data entry screen, you simply enter the tolerance of the input supply (in this case, 12 V +/-2 V = 10-V min, 14-V max input) and the desired output specification (3.3 V, 2 A). Several choices using

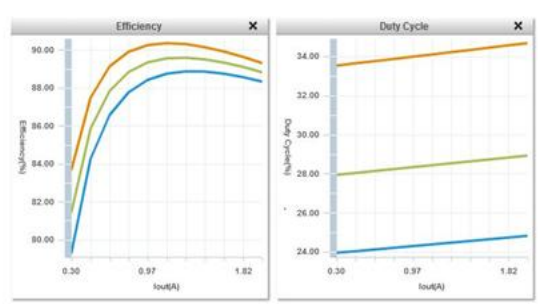
different ICs will be offered, and you can select from these based on whether you want to optimize cost, size or efficiency.



The output generated will show the complete schematic, bill of materials (external component listings), and typical estimated performance data like efficiency and duty-cycle variation at different operating points. WEBENCH software can generate additional information such as the complete list of suggested components and basic performance estimates, as shown in Figure 10.

Electrical BOM

#	Name	Manufacturer	Part Number	Quantity	Price	Properties	Footprint
1.	Cin	MuRata	GRM31CR61E106KA12L Series= X5R	1	$0.07	Cap= 10.0 µF ESR= 4.0 mOhm VDC= 25.0 V IRMS= 0.0 A	1206 19mm2
2.	Cout	TDK	C2012X5R0J226M Series= X5R	1	$0.06	Cap= 22.0 µF ESR= 1.8 mOhm VDC= 6.3 V IRMS= 0.0 A	0805 13mm2
3.	Css	Kemet	C0805C332K5RACTU Series= X7R	1	$0.01	Cap= 3.3 nF ESR= 332.0 mOhm VDC= 50.0 V IRMS= 319.0 mA	0805 13mm2
4.	L1	TDK	VLC5045T-2R2N	1	$0.18	L= 2.2 µH DCR= 22.0 mOhm	VLC5045 49mm2
5.	Rpg	Vishay-Dale	CRCW0402100KFKED Series= CRCW..e3	1	$0.01	Res= 100.0 kOhm Power= 63.0 mW Tolerance= 1.0%	0402 8mm2
6.	U1	Texas Instruments	TPS62142RGTR	1	$1.15	Switcher	S-PVQFN-N16 36mm2



Example output from WEBENCH Design Tool – Component List and Performance Graphs

Test and measurement of your power converter

When troubleshooting (or simply verifying the proper operation of) a power-supply circuit, you should follow some basic practices to ensure accurate measurements. Because DC/DC switch-mode converters involve fast switching devices (power FETs used in the regulation circuits), as well as large current and voltage transients, improper technique can easily lead to misleading measurements. For example, the input power supply for a circuit being tested on a lab bench might be located a foot or two away from the test board. If current is flowing through a few feet of cable, there can be 10 s or even 100 s of millivolts difference from one end of the cable to the other. This amount of voltage drop can have a noticeable effect on the (perceived) efficiency of the circuit. In general, use larger wires (good conductors with low loss) and shorter lengths of cable wherever possible. When measuring fast signals such as the gate drive or switching nodes in a DC/DC converter, even the conventional 2- to 3-inch-long ground lead on an oscilloscope probe can lead to misleading indications of output ripple and/or transient response ringing. The articles in References 6 and 7 explain some of the procedures associated with testing a power circuit in greater detail.

Power losses, thermal management and basic thermal calculations

While an ideal power conversion circuit is always 100 percent efficient, any real system will have some amount of loss (inefficiency). “Loss” in this case means that some portion of the energy taken from the input is not delivered to the output – and thus translates to heat generated within the power-supply components. Some typical sources of power loss are:

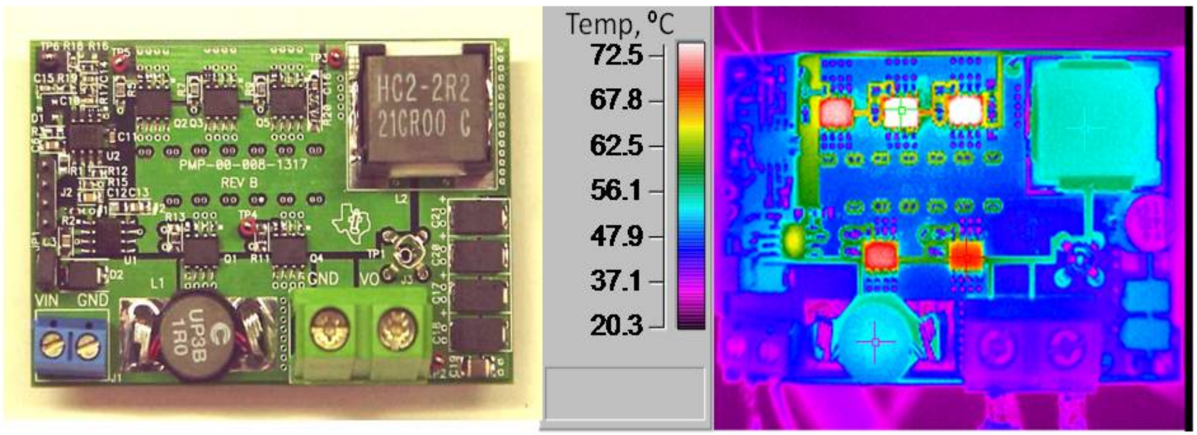
- Ohmic losses in magnetic components (an ideal inductor has zero DCR – a real inductor has finite, nonzero DCR).
- Conduction (ohmic) losses in power-switching devices (FET or BJT).
- Switching losses in FETs and BJTs – energy is consumed just to turn these devices on/off.
- Quiescent/operating currents for the IC devices.

When power loss occurs, it results in heat generation within the semiconductors and passive components. Depending on the physical design of a system (IC packaging, PCB layout and trace widths, airflow, etc.), a

given amount of electrical power loss (Watts dissipated) will translate to a specific amount of heat generated (temperature increase above ambient).

For reliable operation as well as prevention of any potential user safety issues, semiconductor operating temperatures need to stay below the recommended maximum values (e.g. 125ºC). Although in most cases, you will not be able to directly measure the actual semiconductor (die) temperature (because the IC is encapsulated within an external package), there are methods of estimating internal die temperature based on (measurable and/or specified) external temperatures on the PCB surface or external IC package locations.

Figure 11 shows a photograph of a typical mid-power DC/DC converter board next to the thermal image of the circuit during operation. For an ambient temperature of 20ºC, you can see that specific components (power FETs, power inductor) may actually be as much as 50ºC hotter due to operating power losses. This implies that to prevent internal component temperatures from exceeding a specified maximum such as 125ºC, the overall circuit needs to be in an ambient environment of less than 70ºC for reliable operation. See References 8 and 9 for further explanation of the basic thermal calculations required to ensure safe and reliable power-circuit operation. Table 2 lists part numbers for commonly used power management devices.


HC2-2R2
21CR00 C
PMP-00-008-1317
REV B
VIN
GND
GND
VO
UP3B
1R0
Temp, °C
72.5
67.8
62.5
56.1
47.9
37.1
20.3

List of Part Numbers for Commonly used Power Management Devices

Part Number	Package Type	Package Code	Description
BQ24090DGQT	MSOP	DGQ	1A output, Single-Cell Li-Ion Linear Charger
BQ24172RGYT	VQFN	RGY	Adjustable output Switch-Mode charger for 1, 2, or 3-cell Li-Ion Batteries
LM317KTTR	SFM	KTT	3-TERMINAL ADJUSTABLE REGULATOR
LP2951DR	SOIC		Low Power, Single Output LDO, 100mA, Fixed(3.3V), Wide Vin Range
MC34063AP	PDIP		1.5-A Boost/Buck/Inverting Switching Regulator
REG711EA-3.3/250	VSSOP		1.8-5.5Vin 3.3Vout 50mA Switched-Cap DC/DC Converter
REG711EA-5/2K5	VSSOP		2.7-5.5Vin 5Vout 50mA Switched-Cap DC/DC Converter
TL2575HV-ADJIKV	TO	KV	Up to 60V Vin, 1-A Simple Step-Down Switching Voltage Regulators
TL2575HV-ADJIN	PDIP		1A Simple Step Down Voltage Reg
TL7660IP	SOIC	D	CMOS Voltage Converter
TLV70233DBVT	SOT	DBV	300-mA, Low-IQ, Low-Dropout Regulator
TPS40211DGQ	VSSOP	DGQ	Wide Input Range Current Mode Boost Controller
TPS54260DGQ	VSSOP	DGQ	3.5V to 60V Input, 2.5A Step-Down Converter with Eco-Mode
TPS5430DDA	SOIC	DDA	3-A, WIDE INPUT RANGE, STEP-DOWN SWIFT™ CONVERTER
TPS54331D	SOIC	D	3A, 28V INPUT, STEP DOWN SWIFT™ DC/DC CONVERTER WITH ECO-MODE™
TPS5450DDA	SOIC	DDA	5-A, WIDE INPUT RANGE, STEP-DOWN SWIFT™ CONVERTER
TPS60302DGSR	VSSOP	DGS	Single-Cell to 3.0V/3.3V, 20mA Dual Output, High Efficiency Charge Pump
TPS60400DBVT	SOT	DBV	60mA Charge Pump Voltage Inverter with Variable Switching Frequency
TPS61029DRCT	VSON	DRC	Adjustable, 1.8-A Switch, 96% Efficient Boost Converter with Down-Mode, QFN-10
TPS61040DBVR	SOT	DBV	28-V, 400-mA Switch Boost Converter in SOT-23 for LCD and White LED Applications
TPS63020DSJT	VSON	DSJ	HIGH EFFICIENCY SINGLE INDUCTOR BUCK-BOOST CONVERTER WITH 4-A SWITCHES
TPS7201	PDIP, SOIC		Micropower, Low-Drop out Regulator, Adjustable Output
TPS7250	PDIP, SOIC		Micropower, Low-Drop out Regulator, Fixed 5.0V Output
TPS74401KTWT	SFM	KTW	Single Output LDO, 3.0A, Adj.(0.8 to 3.3V), Fast Transient Response, Programmable Soft Start
TPS767D301PWP	TSSOP	PWP	DUAL-OUTPUT LOW-DROPOUT VOLTAGE REGULATORS
TPS79601KTTT	SFM	KTW	Single Output LDO, 1.0A, Adj.(1.2 to 5.5V), Low Noise, High PSRR
Red = parts used in teaching labs			

Table 2.

References

- 1. Lee, Bang S. "Understanding the Terms and Definitions of LDO Voltage Regulators." TI literature No. SLVA079. http://www.ti.com/lit/an/slva079/slva079.pdf

- 2. Brown, Marty. Power Supply Cookbook, Second Edition. Newnes, 2001. http://books.google.com/books?id=zWcpOJNz7n8C&printsec=frontcover&source=gbs_atb#v=onepage&q&f=false

- 3. Lenk, Ron. Practical Design of Power Supplies. McGraw-Hill, IEEE Press, 1998. http://books.google.com/books/about/Practical_design_of_power_supplies.html?id=leseAQAAIAAJ

- 4. Lester, Scot. "Component and Layout Considerations for DC/DC Converters." TI Power Supply Design Seminar 1700, 2007. http://focus.ti.com/download/trng/docs/seminar/2007%20PPM%20Seminar%20White%20Papers.zip

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- 7. Naik, Jatan. "Performing Accurate PFM Mode Efficiency Measurements." TI literature No. SLVA236. http://www.ti.com/lit/an/slva236/slva236.pdf

- 8. Hunter, Bruce, and Patrick Rowland. "Linear Regulator Design Guide for LDOs." TI literature No. SLVA118A.

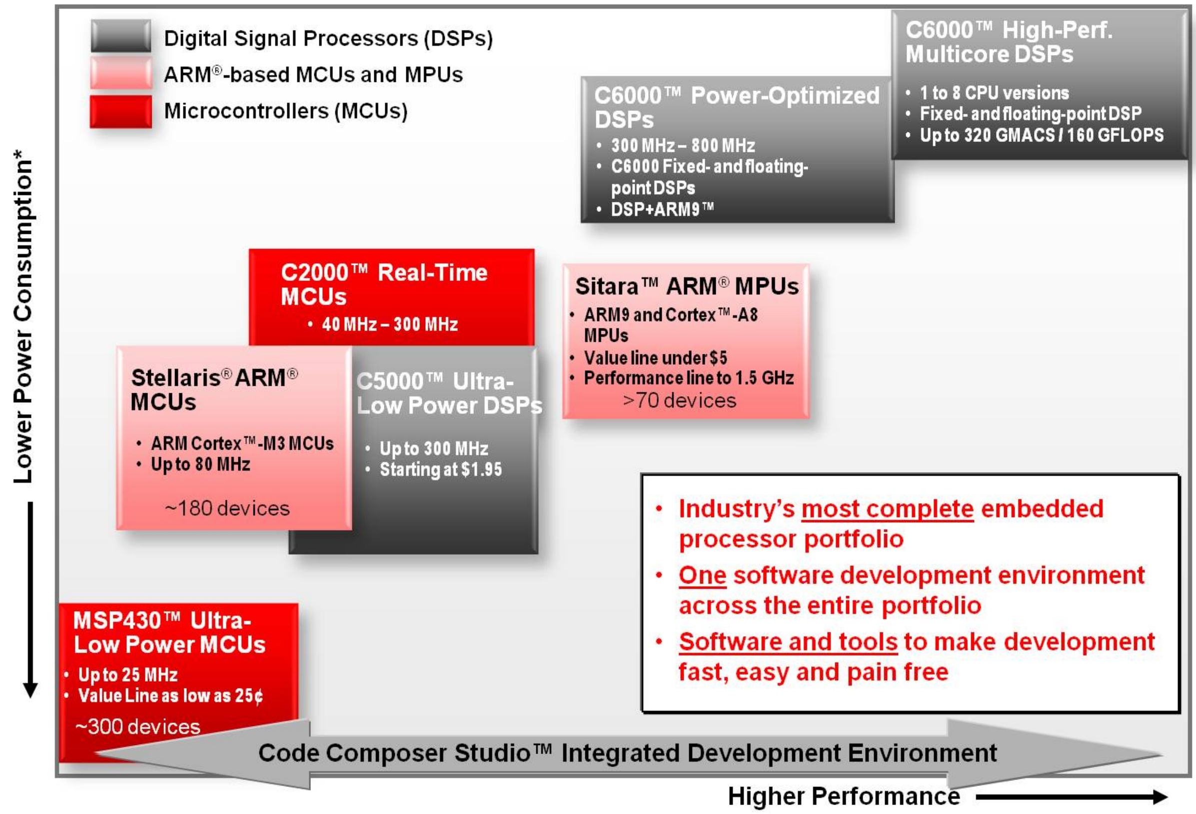
http://www.ti.com/lit/an/slva118a/slva118a.pdf

- 9. Mauney, Charles. "Thermal Considerations for Surface Mount Layouts." TI Portable Power Supply Design Seminar, 2006. http://focus.ti.com/download/trng/docs/seminar/Topic%2010%20-%20Thermal%20Design%20Consideration%20for%20Surface%20Mount%20Layouts%20.pdf
- 10. Sengupta, Upal. "PWM and PFM Operation of DC/DC Converter for Portable Applications." TI Power Supply Design Seminar 1700, 2007. http://focus.ti.com/download/trng/docs/seminar/2007%20PPM%20Seminar%20White%20Papers.zip

Embedded Processors
This module introduces the embedded processor section of the senior project textbook.

Introduction

Texas Instruments has a wide range of embedded processors available to design into your project. Your choices include virtually everything from very low cost to very high performance, as well as a new performance metric called power dissipation. Figure 1 gives a quick overview of our embedded processor product line.



You should be able to complete your project using one of the following product families:

- The MSP430™ ultra-low-power system microcontroller family.
- C2000™ microcontrollers used in control systems.
- ARM devices (specifically the M3/4 microcontrollers).
- The C5000™ low-power signal-processing solution.

TI's other embedded processors fall beyond the scope of a typical two-semester senior project. We will spend time on the families listed here in the following chapters, focusing on those embedded processors that will best fit your project.

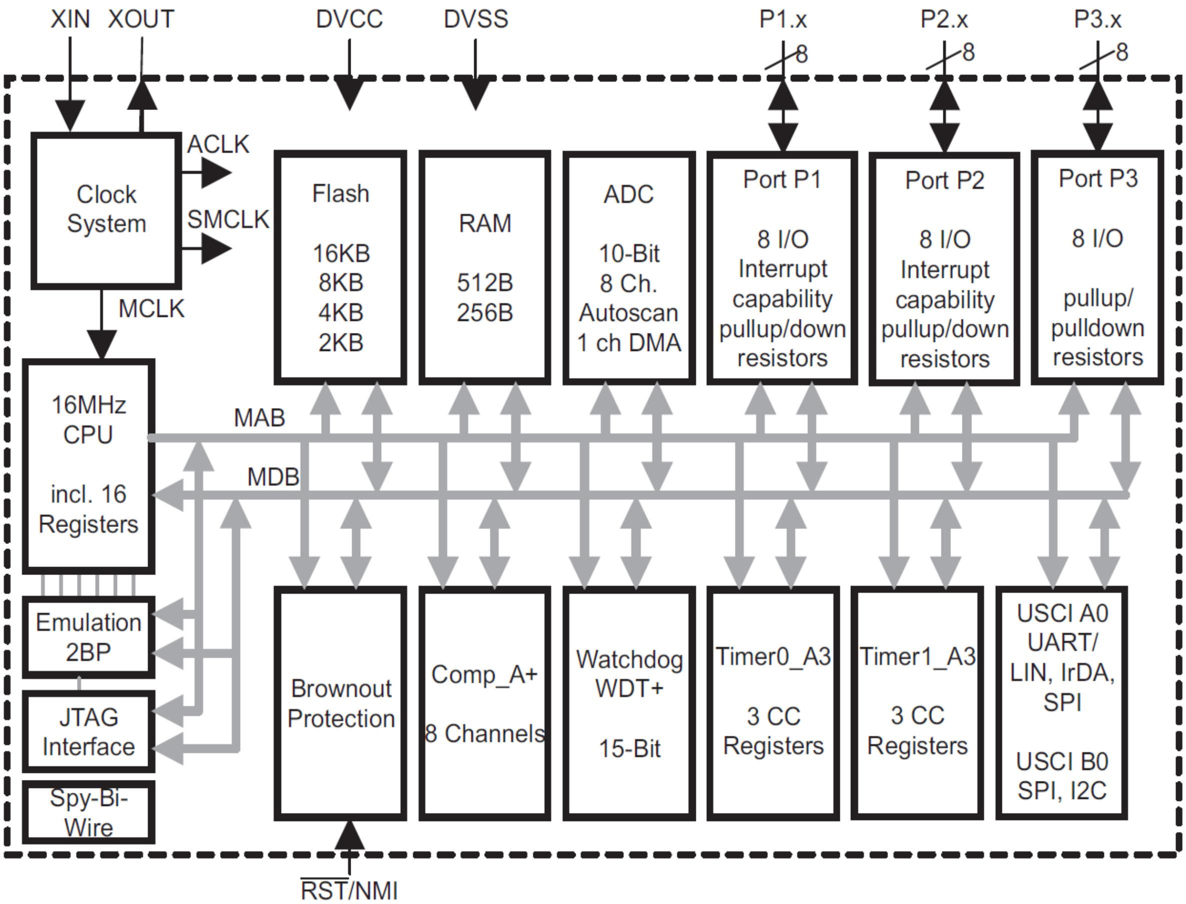
Remember, the best way to take advantage of an embedded processor is to use an evaluation module (EVM). You can find these listed for various processors on [www.ti.com.](http://www.ti.com)

Overview of the MSP430™ Microcontroller from Texas instruments
This module gives a brief overview of the MSP430™ microcontroller, how to read a data sheet for an MSP430™ microcontroller, and how to pick the right one for some sample applications. This module is one of many in a textbook designed to help seniors select TI products for use in their senior project.

MSP430™ microcontrollers

MSP430™ microcontrollers (MCUs) from Texas Instruments are 16-bit, RISC-based, mixed-signal processors designed specifically for ultra-low power. MSP430 MCUs have the right mix of analog and digital integrated intelligent peripherals, ease of use, low cost and lowest power consumption for thousands of applications ranging from simple sensor designs to complex electricity meters.

To get a better idea of what the MSP430 MCU is and how you can use it to solve a system design need or application problem, let's take a look at a typical block diagram for a device. Figure 1 is the device block diagram for the MSP430G2553, one of the MSP430 Value Line devices.



The purpose of the block diagram is to provide a high-level reference of the integration and feature set found in a given device. You can find the block diagram for any MSP430 MCU in the data sheets at [www.msp430.com.](http://www.msp430.com)

The block diagram contains key features of the device that can help you quickly identify if an MSP430 MCU is a fit for a given application need. There are a few features you will need to consider:

- Integrated memory:
    - Includes both volatile (RAM) and nonvolatile (flash) sizes.
    - When multiple values are listed, it shows which device memory size variants are available with the same peripherals.
- General-purpose I/O pins:

    - The MSP430G2553 has up to 24 I/Os available: eight Port1 (P1), eight P2 and eight P3 I/Os.
        - Package-dependent: Check the pinout for the total number.
    - All pins have configurable integrated pullup or pulldown resistors.
    - P1 and P2 I/Os when inputs can provide an interrupt to the CPU.
- CPU and emulation capabilities:
    - 16 MHz is the maximum CPU clock speed for the MSP430G2553.
    - Integrated emulation for the MSP430G2553 has two hardware breakpoints (2BP) for use when debugging.
- Simplified clock system:
    - One external clock source on XIN/XOUT can be sourced.
    - The internal clock tree provides three clock tree branches.
- Digital and analog peripheral mix. The MSP430G2553 device includes:
    - 10-bit, eight-channel analog-to-digital converter (ADC) with internal voltage reference for voltage measurement (sensors, power rails, etc).
    - Comp_A+: eight-channel analog comparator with internal voltage reference for simple measurements or voltage threshold detection.
    - WDT+: watchdog timer for resetting the CPU in case of timeout (can also be used as a simple interval timer generating an interrupt).
    - Timer0,1_A3: two 16-bit general-purpose timers, each with three capture-compare (CC) I/Os.
    - USCI (A0/B0): universal serial communication interface module capable of providing standard UART, SPI and I2C communication protocols used to interface with external digital devices (sensors, data converters, radio ICs).

Figure 2 is the corresponding pinout also found in each device data sheet for the MSP430G2553. Here you can see exactly how peripheral functions are mapped onto the multiplexed I/Os of the device. Each I/O pin can be configured in software to provide the desired pin function for a given I/O based on its internal connectivity.

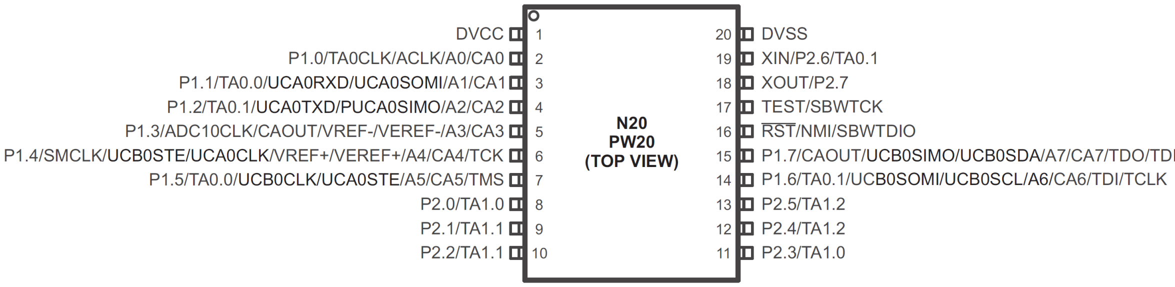


Figure 2 also shows the necessary power-supply connections (DVCC, DVSS), programmer/debugging tool connections (SBWTCK, SBWTDIO), and general I/O and peripheral connections (P3.1, TA1.0, CA2, UCB0SDA). When beginning any design with the MSP430 MCU, reviewing the given device's block diagram and package pinout can provide a great guide to what is possible, as well as any constraints (such as memory size or pinout limitations).

Connecting the MSP430 MCU in any system is, in most cases, very straightforward. The first consideration should be the power-supply requirements. Most MSP430 devices operate at 1.8 V to 3.6 V, so a typical 3-V supply will work great. Connecting the JTAG to support device memory programming and debugging is also important. For MSP430G2xxx devices, there are two possibilities: standard four-wire JTAG or MSP430 MCU-specific Spy-Bi-Wire (SBW, or two-wire JTAG). Both interfaces are acceptable for programming and debugging application code. The main advantage of the four-wire mode is speed. The main advantage of the two-wire SBW mode is reduced pin-connection requirements.

Figure 3 is an example schematic thatshows the baseline connections for the MSP430G2553, as well as some examples of other connections that can be made to the I/Os and integrated peripherals.

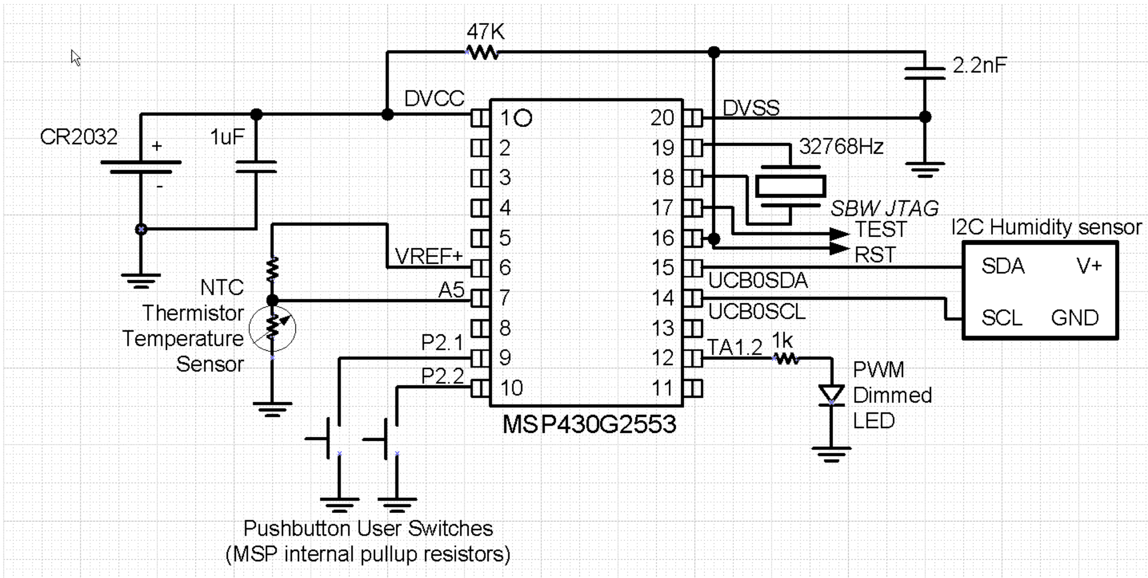


Figure 3 shows the connections of the MSP430G2553 in a typical sensor interface application. In this example, the MSP430G2553's integrated ADC10 is used to measure an analog signal via a thermistor that changes resistance as temperature increases or decreases, and also interfaces using an I2C bus from the USCI module to an external humidity sensor. In addition, a 32.768-kHz watch crystal keeps accurate timing; two switches, along with one PWM-controlled LED, provide a simple user interface. To save power from the 3-V coin cell battery, when not in use the humidity sensor and thermistor ladder can be powered off using a general-purpose I/O (P2.5) and the internal voltage reference (VREF+), respectively.

Now that we've covered the basics and how to understand the capabilities of a given MSP430 device, let’s look more closely at the documentation and how to use it most effectively. MSP430 device documentation can be broken up into three main categories:

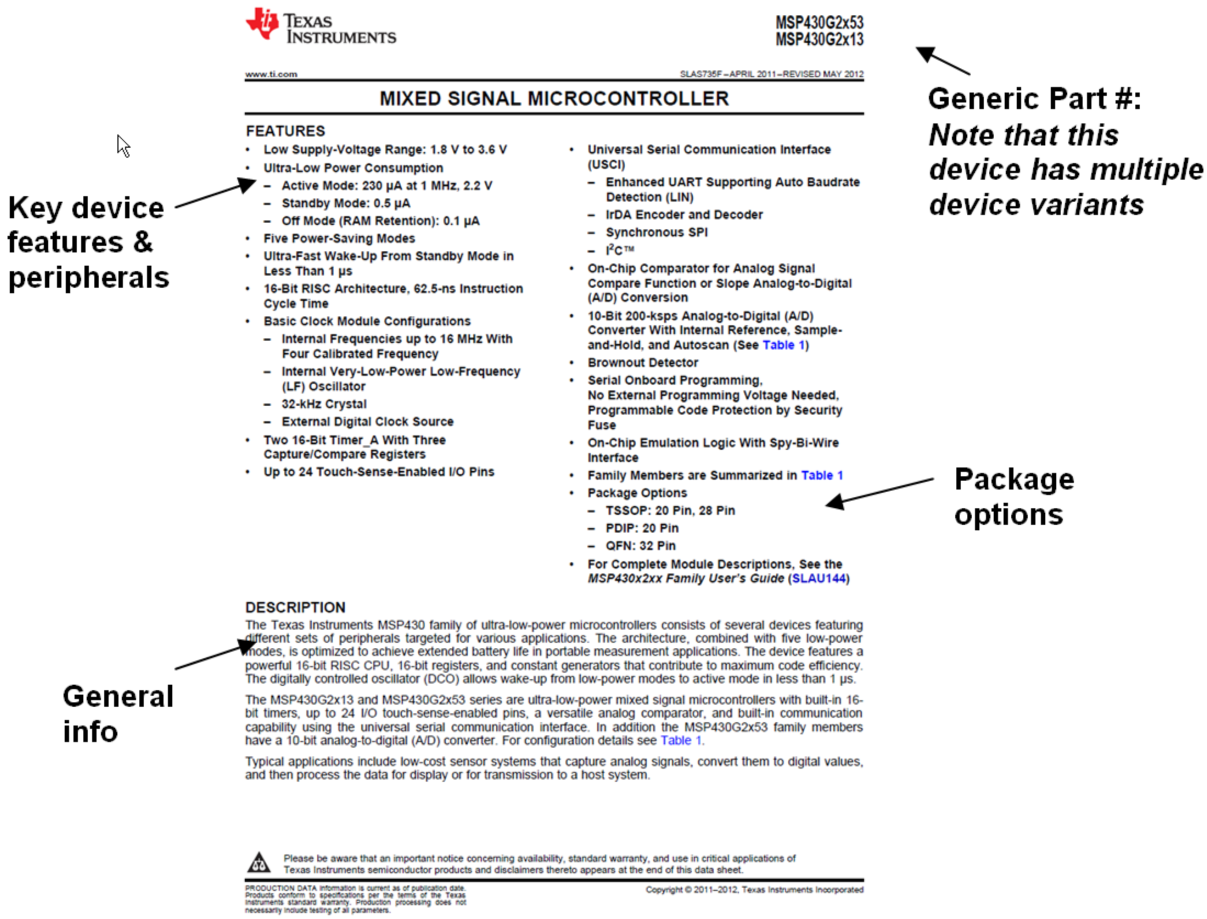
- Device-specific data sheet (e.g., MSP430G2553 data sheet.) Here, you will find anything device-specific: pinouts, block diagrams, absolute operating conditions (supply voltage and operating temperature ranges), electrical parameters and performance tolerances (power consumption, ADC accuracy, and internal clock minimum and maximum frequencies).

- Device family user’s guide (e.g., MSP430x2xx family user's guide). This document contains information applicable to all devices in a family: peripheral detailed descriptions, register and bit function definitions, CPU and instruction set, power mode definitions and settings. Some peripherals included in the user’s guide will not be present in a given device, as it is intended to cover all peripherals within a given family.

- Device-specific errata sheet (e.g., MSP430G2553 device errata sheet). The errata sheet is a critical document that lists any device bugs that can affect a given use-case along with potential workarounds. Errata can vary by device as well as device revisions.

You can find these documents, as well as additional reference material such as application notes, example code and development tool documentation, by navigating to the device-specific product folder (e.g., MSP430G2553 product folder). Here, you can find the latest information as well as links to all pertinent documentation and software to aid your design efforts.

Arguably, the most valuable document is the device-specific data sheet. We have already looked at two core aspects (pinout and block diagram), but let’s dive a bit deeper into the information provided. The front page of the data sheet is designed to highlight all of the key aspects of the device organized into bulleted lists (Figure 4). It is comprehensive, showing typical power consumption, clock system capabilities, peripheral mix and package options.



TEXAS INSTRUMENTS

MSP430G2x53
MSP430G2x13

www.ti.com

SLAS735F – APRIL 2011 – REVISED MAY 2012

MIXED SIGNAL MICROCONTROLLER

FEATURES

- Low Supply-Voltage Range: 1.8 V to 3.6 V
- Ultra-Low Power Consumption
  - Active Mode: 230 µA at 1 MHz, 2.2 V
  - Standby Mode: 0.5 µA
  - Off Mode (RAM Retention): 0.1 µA
- Five Power-Saving Modes
- Ultra-Fast Wake-Up From Standby Mode in Less Than 1 µs
- 16-Bit RISC Architecture, 62.5-ns Instruction Cycle Time
- Basic Clock Module Configurations
  - Internal Frequencies up to 16 MHz With Four Calibrated Frequency
  - Internal Very-Low-Power Low-Frequency (LF) Oscillator
  - 32-kHz Crystal
  - External Digital Clock Source
- Two 16-Bit Timer_A With Three Capture/Compare Registers
- Up to 24 Touch-Sense-Enabled I/O Pins
- Universal Serial Communication Interface (USCI)
  - Enhanced UART Supporting Auto Baudrate Detection (LIN)
  - IrDA Encoder and Decoder
  - Synchronous SPI
  - I²C™
- On-Chip Comparator for Analog Signal Compare Function or Slope Analog-to-Digital (A/D) Conversion
- 10-Bit 200-ksps Analog-to-Digital (A/D) Converter With Internal Reference, Sample-and-Hold, and Autoscan (See Table 1)
- Brownout Detector
- Serial Onboard Programming, No External Programming Voltage Needed, Programmable Code Protection by Security Fuse
- On-Chip Emulation Logic With Spy-Bi-Wire Interface
- Family Members are Summarized in Table 1
- Package Options
  - TSSOP: 20 Pin, 28 Pin
  - PDIP: 20 Pin
  - QFN: 32 Pin
- For Complete Module Descriptions, See the *MSP430x2xx Family User's Guide* (SLAU144)

DESCRIPTION

The Texas Instruments MSP430 family of ultra-low-power microcontrollers consists of several devices featuring different sets of peripherals targeted for various applications. The architecture, combined with five low-power modes, is optimized to achieve extended battery life in portable measurement applications. The device features a powerful 16-bit RISC CPU, 16-bit registers, and constant generators that contribute to maximum code efficiency. The digitally controlled oscillator (DCO) allows wake-up from low-power modes to active mode in less than 1 µs.

The MSP430G2x13 and MSP430G2x53 series are ultra-low-power mixed signal microcontrollers with built-in 16-bit timers, up to 24 I/O touch-sense-enabled pins, a versatile analog comparator, and built-in communication capability using the universal serial communication interface. In addition the MSP430G2x53 family members have a 10-bit analog-to-digital (A/D) converter. For configuration details see Table 1.

Typical applications include low-cost sensor systems that capture analog signals, convert them to digital values, and then process the data for display or for transmission to a host system.

Please be aware that an important notice concerning availability, standard warranty, and use in critical applications of Texas Instruments semiconductor products and disclaimers thereto appears at the end of this data sheet.

PRODUCTION DATA information is current as of publication date. Products conform to specifications per the terms of the Texas Instruments standard warranty. Production processing does not necessarily include testing of all parameters.

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This information is a great start, but is targeted as more of a marketing message than a reference. Going beyond the first page is critical to fully assess the given device's capabilities and its limitations. Looking beyond the first page begins to yield the information needed to really design a system with the MSP430 MCU. This begins with the available options for the device and variants. For example, there are 40 device and orderable part number variants for the MSP430G2553 device. These variants provide different mixes of flash or RAM, peripherals available, number of I/Os supported, and package options such as DIP or surface-mount options.

While all information in a data sheet should be considered important, we recommend focusing on these areas when reviewing a data sheet for a specific MSP430 MCU:

- Supported interrupt sources, corresponding flags and priority (Figure 5).

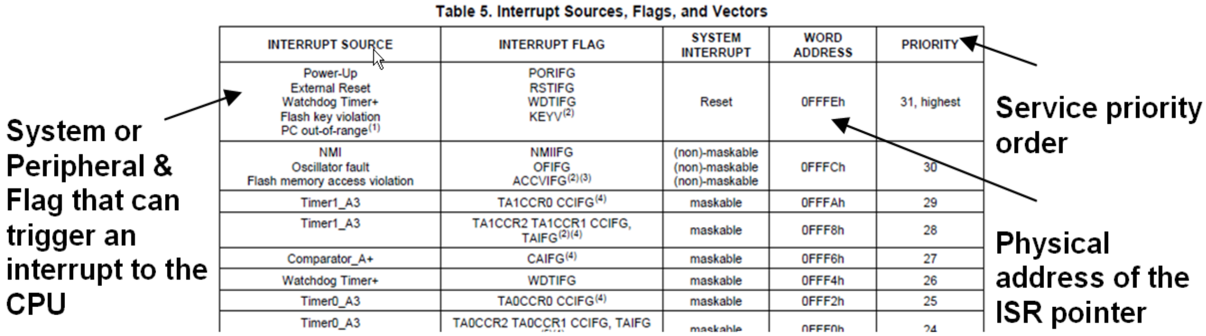


Table 5. Interrupt Sources, Flags, and Vectors

INTERRUPT SOURCE	INTERRUPT FLAG	SYSTEM INTERRUPT	WORD ADDRESS	PRIORITY
Power-Up External Reset Watchdog Timer+ Flash key violation PC out-of-range(1)	PORIFG RSTIFG WDTIFG KEYV(2)	Reset	0FFFEh	31, highest
NMI Oscillator fault Flash memory access violation	NMIIFG OFIFG ACCVIFG(2)(3)	(non)-maskable (non)-maskable (non)-maskable	0FFFCh	30
Timer1_A3	TA1CCR0 CCIFG(4)	maskable	0FFFAh	29
Timer1_A3	TA1CCR2 TA1CCR1 CCIFG, TAIFG(2)(4)	maskable	0FFF8h	28
Comparator_A+	CAIFG(4)	maskable	0FFF6h	27
Watchdog Timer+	WDTIFG	maskable	0FFF4h	26
Timer0_A3	TA0CCR0 CCIFG(4)	maskable	0FFF2h	25
Timer0_A3	TA0CCR2 TA0CCR1 CCIFG, TAIFG	maskable	0FFF0h	24

- Calibration data such as internal clock defaults and ADC offset/gain settings (Figure 6).

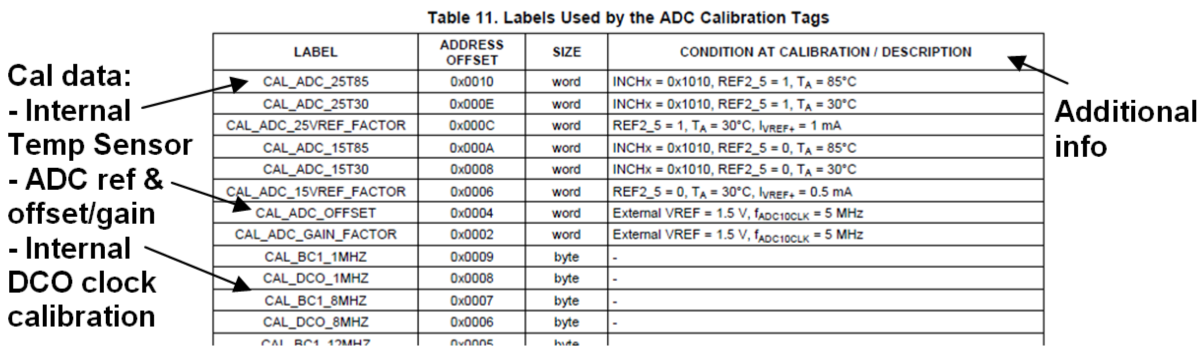


Table 11. Labels Used by the ADC Calibration Tags

LABEL	ADDRESS OFFSET	SIZE	CONDITION AT CALIBRATION / DESCRIPTION
CAL_ADC_25T85	0x0010	word	INCHx = 0x1010, REF2_5 = 1, T_A = 85°C
CAL_ADC_25T30	0x000E	word	INCHx = 0x1010, REF2_5 = 1, T_A = 30°C
CAL_ADC_25VREF_FACTOR	0x000C	word	REF2_5 = 1, T_A = 30°C, I_{VREF+} = 1 mA
CAL_ADC_15T85	0x000A	word	INCHx = 0x1010, REF2_5 = 0, T_A = 85°C
CAL_ADC_15T30	0x0008	word	INCHx = 0x1010, REF2_5 = 0, T_A = 30°C
CAL_ADC_15VREF_FACTOR	0x0006	word	REF2_5 = 0, T_A = 30°C, I_{VREF+} = 0.5 mA
CAL_ADC_OFFSET	0x0004	word	External VREF = 1.5 V, $f_{ADC10CLK}$ = 5 MHz
CAL_ADC_GAIN_FACTOR	0x0002	word	External VREF = 1.5 V, $f_{ADC10CLK}$ = 5 MHz
CAL_BC1_1MHZ	0x0009	byte	-
CAL_DCO_1MHZ	0x0008	byte	-
CAL_BC1_8MHZ	0x0007	byte	-
CAL_DCO_8MHZ	0x0006	byte	-
CAL_BC1_12MHZ	0x0005	byte	

- Timer functions and pinouts for each capture-compare I/O (Figure 7).

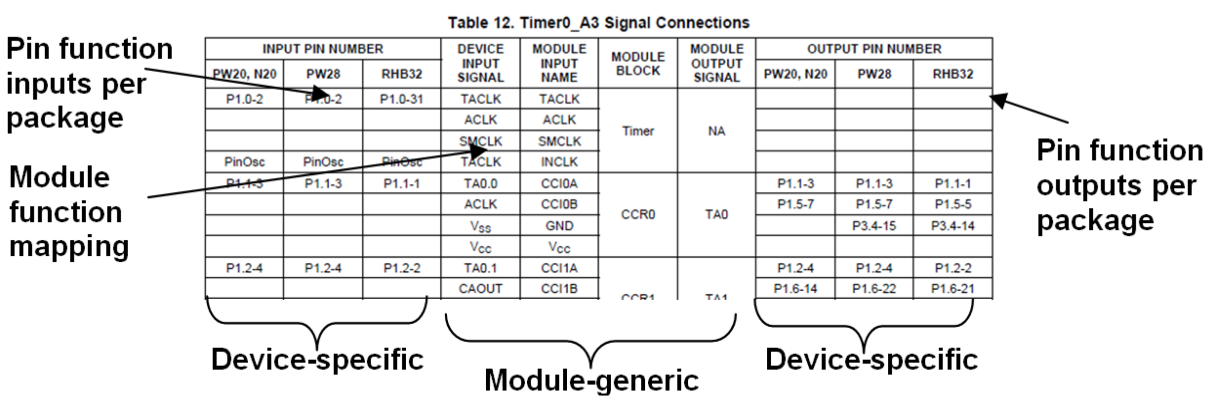


Table 12. Timer0_A3 Signal Connections

INPUT PIN NUMBER			DEVICE INPUT SIGNAL	MODULE INPUT NAME	MODULE BLOCK	MODULE OUTPUT SIGNAL	OUTPUT PIN NUMBER		
PW20, N20	PW28	RHB32					PW20, N20	PW28	RHB32
P1.0-2	P1.0-2	P1.0-31	TACLK	TACLK	Timer	NA			
			ACLK	ACLK					
			SMCLK	SMCLK					
PinOsc	PinOsc	PinOsc	TACLK	INCLK					
P1.1-3	P1.1-3	P1.1-1	TA0.0	CCI0A	CCR0	TA0	P1.1-3	P1.1-3	P1.1-1
			ACLK	CCI0B			P1.5-7	P1.5-7	P1.5-5
			V_{SS}	GND				P3.4-15	P3.4-14
			V_{CC}	V_{CC}					
P1.2-4	P1.2-4	P1.2-2	TA0.1	CCI1A	CCR1	TA1	P1.2-4	P1.2-4	P1.2-2
			CAOUT	CCI1B			P1.6-14	P1.6-22	P1.6-21

- Absolute maximum ratings and recommended operating conditions, including voltage and temperature, as well as CPU clock speeds vs. Vcc (Figure 8).

Absolute Maximum Ratings(1)

Voltage applied at V_{CC} to V_{SS}		–0.3 V to 4.1 V
Voltage applied to any pin(2)		–0.3 V to V_{CC} + 0.3 V
Diode current at any device pin		±2 mA
Storage temperature range, T_{stg} (3)	Unprogrammed device	–55°C to 150°C
	Programmed device	–55°C to 150°C

Absolute pin voltage, current & temperature limitations

Recommended Operating Conditions

			MIN	NOM	MAX	UNIT
V_{CC}	Supply voltage	During program execution	1.8		3.6	V
		During flash programming/erase	2.2		3.6	
V_{SS}	Supply voltage			0		V
T_A	Operating free-air temperature	I version	–40		85	°C
f_{SYSTEM}	Processor frequency (maximum MCLK frequency using the USART module)(1)(2)	V_{CC} = 1.8 V, Duty cycle = 50% ± 10%	dc		6	MHz
		V_{CC} = 2.7 V, Duty cycle = 50% ± 10%	dc		12	
		V_{CC} = 3.3 V, Duty cycle = 50% ± 10%	dc		16	

System frequency (CPU clock) vs Vcc

- Performance specifications for power consumption, analog accuracy, clock tolerances, etc. (Current consumption and ADC performance excerpts shown in Figure 9).

Low-Power Mode Supply Currents (Into V_{CC}) Excluding External Current

over recommended ranges of supply voltage and operating free-air temperature (unless otherwise noted)(1) (2)

PARAMETER		TEST CONDITIONS	T_A	V_{CC}	MIN	TYP	MAX	UNIT
$I_{LPM0,1MHz}$	Low-power mode 0 (LPM0) current(3)	f_{MCLK} = 0 MHz, f_{SMCLK} = f_{DCO} = 1 MHz, f_{ACLK} = 32768 Hz, BCSCTL1 = CALBC1_1MHZ, DCOCTL = CALDCO_1MHZ, CPUOFF = 1, SCG0 = 0, SCG1 = 0, OSCOFF = 0	25°C	2.2 V		56		µA
I_{LPM2}	Low-power mode 2 (LPM2) current(4)	f_{MCLK} = f_{SMCLK} = 0 MHz, f_{DCO} = 1 MHz, f_{ACLK} = 32768 Hz, BCSCTL1 = CALBC1_1MHZ, DCOCTL = CALDCO_1MHZ, CPUOFF = 1, SCG0 = 0, SCG1 = 1, OSCOFF = 0	25°C	2.2 V		22		µA
$I_{LPM3,LFXT1}$	Low-power mode 3 (LPM3) current(4)	f_{DCO} = f_{MCLK} = f_{SMCLK} = 0 MHz, f_{ACLK} = 32768 Hz, CPUOFF = 1, SCG0 = 1, SCG1 = 1, OSCOFF = 0	25°C	2.2 V		0.7	1.5	µA

10-Bit ADC, Linearity Parameters (MSP430G2x53 Only)

over recommended ranges of supply voltage and operating free-air temperature (unless otherwise noted)

PARAMETER		TEST CONDITIONS	V_{CC}	MIN	TYP	MAX	UNIT
E_I	Integral linearity error		3 V			±1	LSB
E_D	Differential linearity error		3 V			±1	LSB
E_O	Offset error	Source impedance R_S < 100 Ω	3 V			±1	LSB
E_G	Gain error		3 V		±1.1	±2	LSB
E_T	Total unadjusted error		3 V		±2	±5	LSB

- Port schematics and pin function tables that detail exactly how to select a given multiplexed function on a given pin using the I/O control registers (Figure 10).

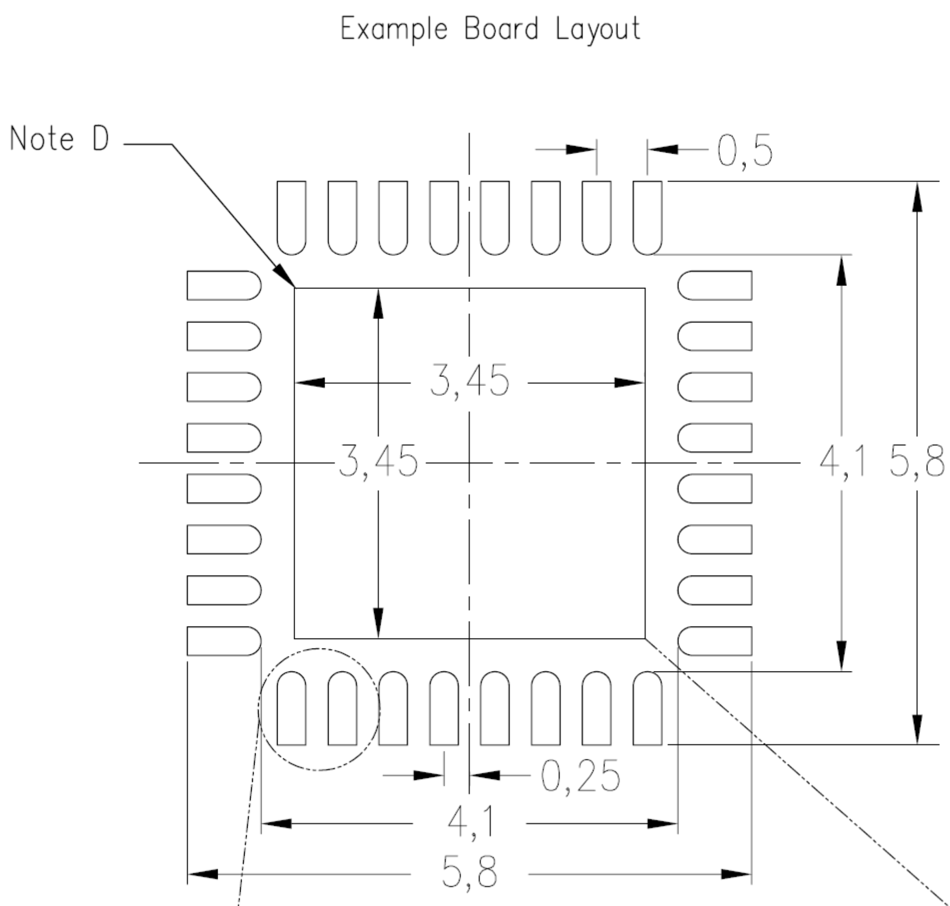
Table 18. Port P1 (P1.4) Pin Functions

Port pin function options

PIN NAME (P1.x)	x	FUNCTION	CONTROL BITS / SIGNALS[1]					
			P1DIR.x	P1SEL.x	P1SEL2.x	ADC10AE.x INCH.x=1[2]	JTAG Mode	CAPD.y
P1.4/	4	P1.x (I/O)	I: 0; O: 1	0	0	0	0	0
SMCLK/		SMCLK	1	1	0	0	0	0
UCB0STE/		UCB0STE	from USCI	1	1	0	0	0
UCA0CLK/		UCA0CLK	from USCI	1	1	0	0	0
VREF+[2]/		VREF+	X	X	X	1	0	0
VEREF+[2]/		VEREF+	X	X	X	1	0	0
A4[2]/		A4	X	X	X	1 (y = 4)	0	0
CA4		CA4	X	X	X	0	0	1 (y = 4)
TCK/		TCK	X	X	X	0	1	0
Pin Osc		Capacitive sensing	X	0	1	0	0	0

Specific control register bit settings per function

- Package information providing package tolerances, useful when creating device footprints in schematic/PCB CAD tools (Figure 11).



Now that we have reviewed the MSP430 device documentation and where to find information about what a device can do, let’s walk through the process of actually selecting the part that best suits a given design need.

Let’s start by answering the questions below:

- 1. “What problem am I trying to solve?” This is fundamental. Until you understand this, nothing else can happen. Knowing what problem you face at a system level allows you to identify how the MCU's features can help you solve that problem most efficiently.

- Do analog signals need to be measured, such as a voltage from a strain gauge or an output from a potentiometer? If so, perhaps an integrated ADC is of value. If a simple analog threshold is all you need, an integrated comparator will likely do the trick.
- What is the user interface? Switches likely translate into simple digital interrupt inputs, while displays may require a communication bus such as SPI in order to refresh the data displayed.
- Are time-sensitive signals needed off-chip? Perhaps you need a PWM signal to control a motor’s speed or LED brightness.
- What are the other devices or circuits that the MCU needs to interface with? Identifying potential analog inputs, logic-level digital I/O signals, or communication interfaces such as I2C or UART will all help you find the right MCU to fit the application need.

- 2. “How many 'things' need to be input into the device or driven from the device [as outputs])?” Determining this at a block level for the system, and then at a more detailed MCU pinout level, will clarify exactly how many I/O pins you will need.

- 3. “What are my power-supply requirements/limitations?” This is important, as the MCU supply may impact the overall system design. For example, if powered from a 9-V battery, the MSP430 MCU will need a regulator to bring its supply to within the 1.8- to 3.6-V range.

- 4. “How much memory will my application need?” This is not always obvious, as the software may not yet be written. But if you plan on using existing code, or modifying code already written, you can get an idea of what a given function in software might require in terms of program and data-memory needs. And when you need certain algorithms such as fast Fourier transform or filtering, you can often estimate RAM requirements before ever selecting the device by simulating the functions on a PC.

- 5. “Are any ‘special’ features needed?” For example, do you need a USB interface to a PC? Or a high-resolution ADC (>12 bits) to get a certain system performance? Consider looking for MCUs that offer such features integrated to minimize the system-level design effort and complexity required.

- 6. “Are there any physical design or assembly constraints (package size, pin spacing, PCB or assembly capability)?” Often, the box the final system must fit into is a factor. This can have big implications on package requirements, pin-count limits and PCB design complexity/cost. Also consider testing a final system – the more dense a design or package is with respect to PCB routing, the more challenging it is to assemble and debug. DIPs are easiest, with BGAs being quite challenging.

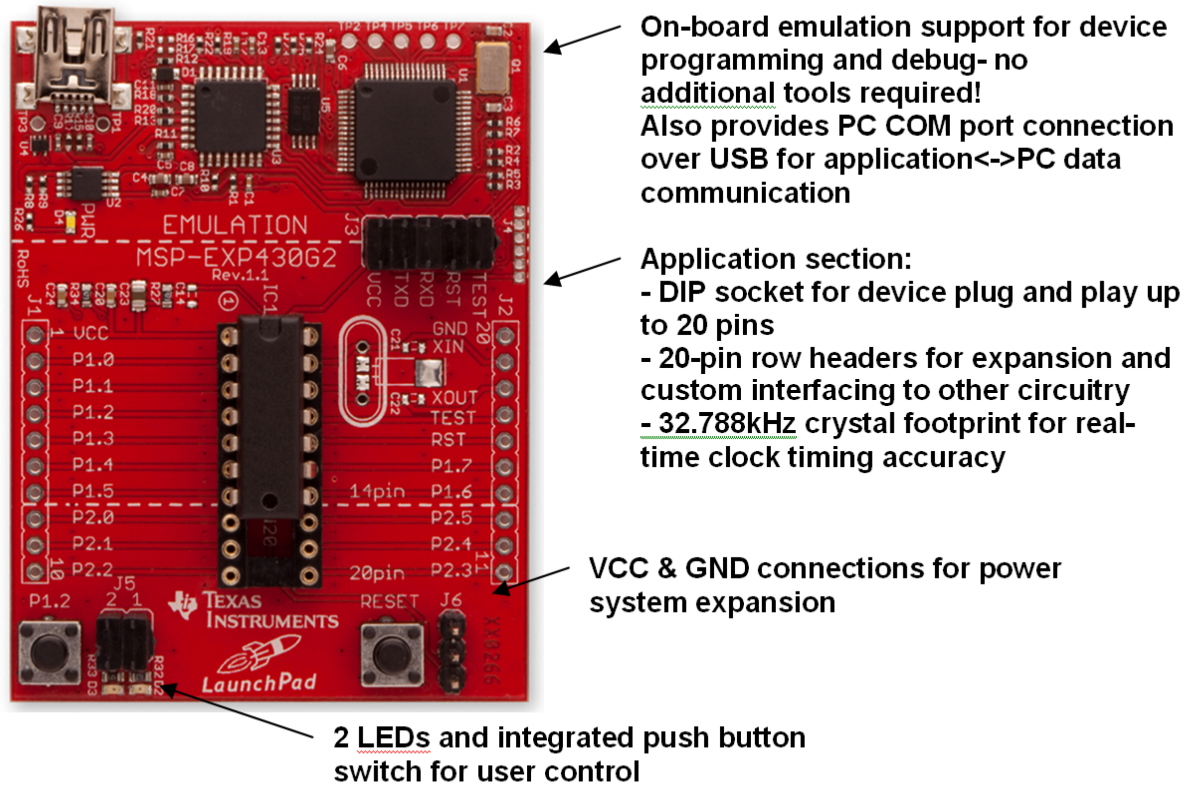
Numerous devices available in the MSP430 family portfolio can meet the given system requirements uncovered in these questions. We've listed a few in Table 1, with their own unique feature sets. A key driver in listing these specific parts is their ease of use. They are available in DIP packages and are supported by a flexible and scalable development tool that can accelerate prototyping of a given application.

Part Number	Package	Flash (KB)	RAM (B)	I/O	Timers	HW I2C?	HW UART?	HW SPI?	Comparator	A/D Converter
MSP430 G2231	PDIP(14)	2	128	10	1 (2CCs)	USI*	NO**	USI*	NO	10-bit, 8channel
MSP430 G2452	PDIP(20)	8	256	16	1 (3CCs)	USI*	NO**	USI*	YES	10-bit, 8channel
MSP430 G2553	PDIP(20)	16	512	16	2 (3CCs each)	YES (USCI)	YES (USCI)	YES (USCI)	YES	10-bit, 8channel

** The USI can be used to support simple SPI or I2C clock/data line transitions. Some user code is still required however to implement the protocol for I2C.*

Table 1. Three MSP430 devices with typical characteristics.

Each of the devices can be used with the MSP430 MCU LaunchPad to provide an easy, intuitive and out-of-the-box development experience (Figure 12).



Solving any design challenge begins by understanding the problem and any constraints that the system may have. Once you have established a clear picture of the problem you need to solve, finding the ideal way to solve that problem – using an MCU – can be straightforward if you understand the capabilities that MCUs offer. Being able to navigate the MSP430 family, its feature set, and the available devices and development tools are keys to success in meeting such a system design challenge.

The C2000™ family of microcontrollers from Texas Instruments
This module gives an overview of the C2000™ family of microcontrollers from Texas Instruments. It includes an overview of the architecture, helpful hints on how to read data sheets and a quick guide to pick the right device for a project. This module is part of a collection of modules aimed at seniors in college who are starting to work on their senior project.

The TMS320C2000™ family of microcontrollers (also known as the C2000™ family) is a product line aimed at high-performance control applications such as motor control, digital power supplies, lighting, renewable energy and smart grid. This family is made up of several subfamilies, with names like:

- C24xx: A 16-bit microcontroller that evolved from the TMS320C2x family of digital signal processors.
- C27xx: A 16-bit microcontroller that is no longer recommended for new designs, so we will not cover it here.
- C28xx: The current family of devices that are 32-bit fixed or floating point, with a robust set of peripherals and I/Os to match the exhaustable need for performance in control applications.

The C28xx family is further divided into:

Delfino™ floating-point MCUs:

- Performance: 100-300 MHz.
- Memory:
    - Up to 512-kB flash.
    - Up to 516-kB SRAM.
- Key peripherals: ADC, PWM, QEP, DMA, SPI, UART, I2C, CAN, EMIF.

Piccolo™ fixed-point MCUs:

-
    - Performance: 40-80 MHz.
    - Memory:

        - 16 to 128-kB flash.
        - 6- to 100-kB SRAM.

    - Key peripherals: ADC, PWM, QEP, DMA, SPI, UART, I2C, CAN, USB.

- Concerto™ C28x core plus M4 ARM processor:

    - Performance:

        - Dual core:

            - Up to 150 MHz 28x CPU.
            - Up to 100 MHz M3 CPU.

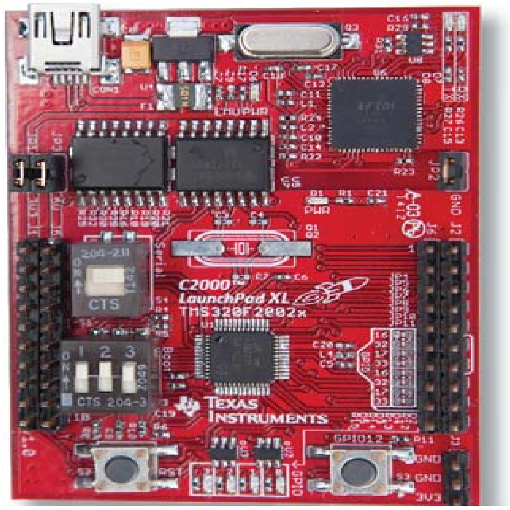
        - Floating-point unit.
        - VCU accelerator.

    - Memory:

        - 16- to 128-kB flash.
        - 6- to 100-kB SRAM.

    - Key peripherals: ADC, PWM, QEP, DMA, SPI, UART, I2C, CAN, USB, EMIF, EMAC.

Let's use the Piccolo MCU to overview the architecture of the family, specifically the TMS320F28027. I have chosen this device because it's the one used in the C2000 LaunchPad™ development tool (shown in Figure 1).

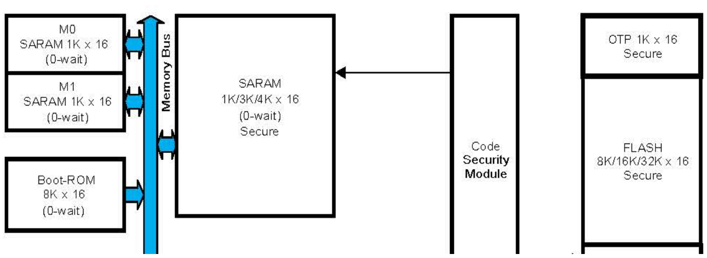


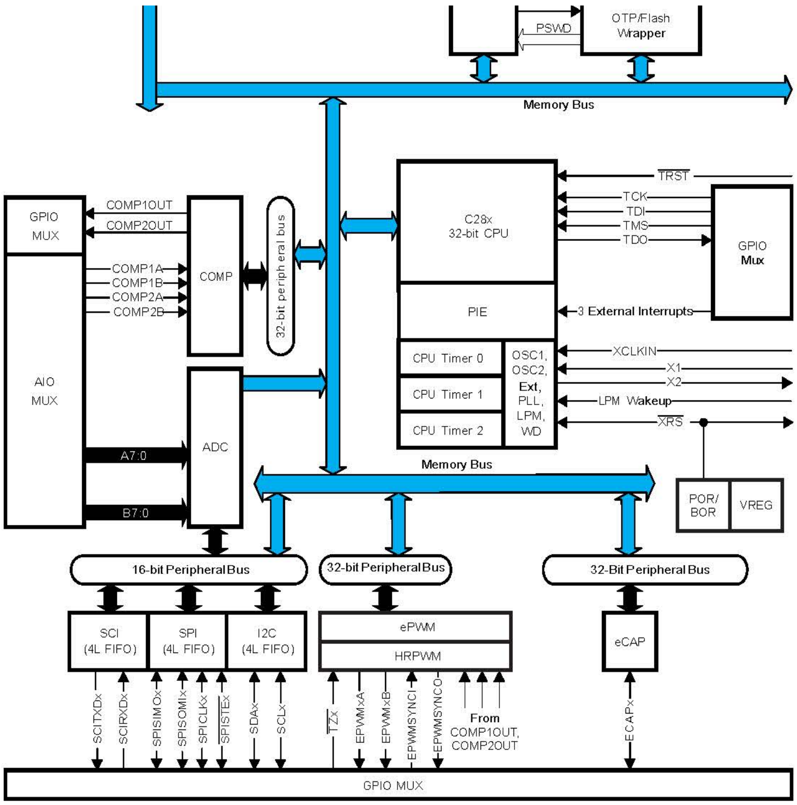
Architecture

A quick look at the CPU:

- High-efficiency 32-bit CPU:
  - Clock frequencies of 40, 50 and 60 MHz.
  - 16-bit and 32-bit hardware multiply and accumulate (MAC) operations, including a dual 16-bit MAC capability.
- Harvard bus architecture: two buses, with one for program and one for data.
- On-chip memory – flash, SARAM, OTP, boot ROM.

Figure 2 is a block diagram of the CPU.





Let’s move on and look at the data sheet.

Data sheet

The data sheet covers the whole family of devices, with their differences being the amount of memory and selection of peripherals and I/Os. Look at these key areas of the data sheet to glean the information you need to select the right part:

- The front page of the data sheet. This will give you an overview of the features of the whole family. You will need to look deeper into the data sheet for specific configurations for each part number in the family. You can also find tools to help you select the right part for your project at www.ti.com.
- The electrical specifications will give you the information you need to plan your power requirements and electrical characteristics.
- The packaging choices and pin descriptions will also be of great use when drawing the schematic, building the prototype, and laying out the printed circuit board.
- The remainder of the data sheet will give you the details you need to successfully design in the device.

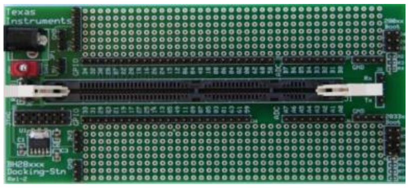
How to pick your device

As with all of our embedded processors, your best choice of a device for your senior project will be one with a development tool. For this family, it could be any one of many evaluation modules (EVMs) available from TI. For example, this chapter is written around the C2000 LaunchPad development tool. Here is a partial list of C2000 EVMs:

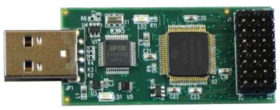
- Control cards (Figure 3).

- Concerto H52C1.
- Piccolo F28027.
- Piccolo F28035.
- Piccolo F28069.
- Delfino F28335.
- Delfino C28436.
- F2808.
- F28044.

- Experimenters kit (Figure 4).



- ControlSTICK (Figure 5).



Application development kits:

- Motor control.
- Digital power.
- Energy and light.

For your senior project, the best of these will probably be the ControlSTICK or the LaunchPad development tool. But don’t ignore the application development kits if they fit your need.

Overview of the ARM Embedded Processors from Texas Instruments
This module is a brief overview of ARM architectures from Texas Instruments, including a guide on how to select the ARM architecture that is right for your application and a deep dive into the Stellaris® ARM Cortex-M architecture.

ARM embedded processors – selecting the right one

ARM embedded processors are ubiquitous. With the vast number of ARM-based processors available, selecting the right one for a senior project can seem daunting. This chapter will help you select the right TI ARM processor.

At a high level, ARM embedded processors can be split into three tiers of performance: the Cortex-A, -R and –M series.

ARM Cortex-A microprocessors

- Highest-performance microprocessors/use external memory.
- For use with a complex operating system.
- Applications:
  - Computing, enterprise, handset, digital home, industrial, wireless infrastructure [http://www.arm.com/products/processors/cortex-a/index.php].

  .
- Author's note:

  Use a Cortex-A device if you:

  - Are ready and willing to develop high-complexity software for your application, including running, debugging and compiling high-level operating systems like Windows, Linux or Android.
  - Are using the microprocessor to program a user interface larger than 7 inches, or wish to display any kind of streaming video on any size display.

        - You wish to program a field bus protocol.

    If you are interested in working with a Cortex-A device from TI, see the BeagleBone website at http://beagleboard.org/bone/.

ARM Cortex-R microcontrollers

- Medium-performance real-time microcontrollers/use integrated memory.
- Designed for safety- and life-critical applications with precise real-time requirements.
- Applications:
    - Storage, enterprise, digital home, cameras, medical, industrial, automotive [http://www.arm.com/products/processors/cortex-r/index.php].
- Author's note:

    Use a Cortex-R device if you:

    - Are ready and willing to develop medium-complexity software, especially if you are interested in safety-critical embedded software development.
    - Want to develop a real transportation or safety application.

    If you are interested in working with a Cortex-R device from TI, see the TMS570 microcontroller USB kit website at http://www.ti.com/tool/tmdx570ls20susb.

ARM Cortex-M microcontrollers

- Lowest-power microcontrollers/use integrated memory.
- Designed for cost- and power-sensitive applications.
- Applications:
    - Smart metering, human interface, industrial, white goods, consumer, portable medical [http://www.arm.com/products/processors/cortex-a/index.php].

.

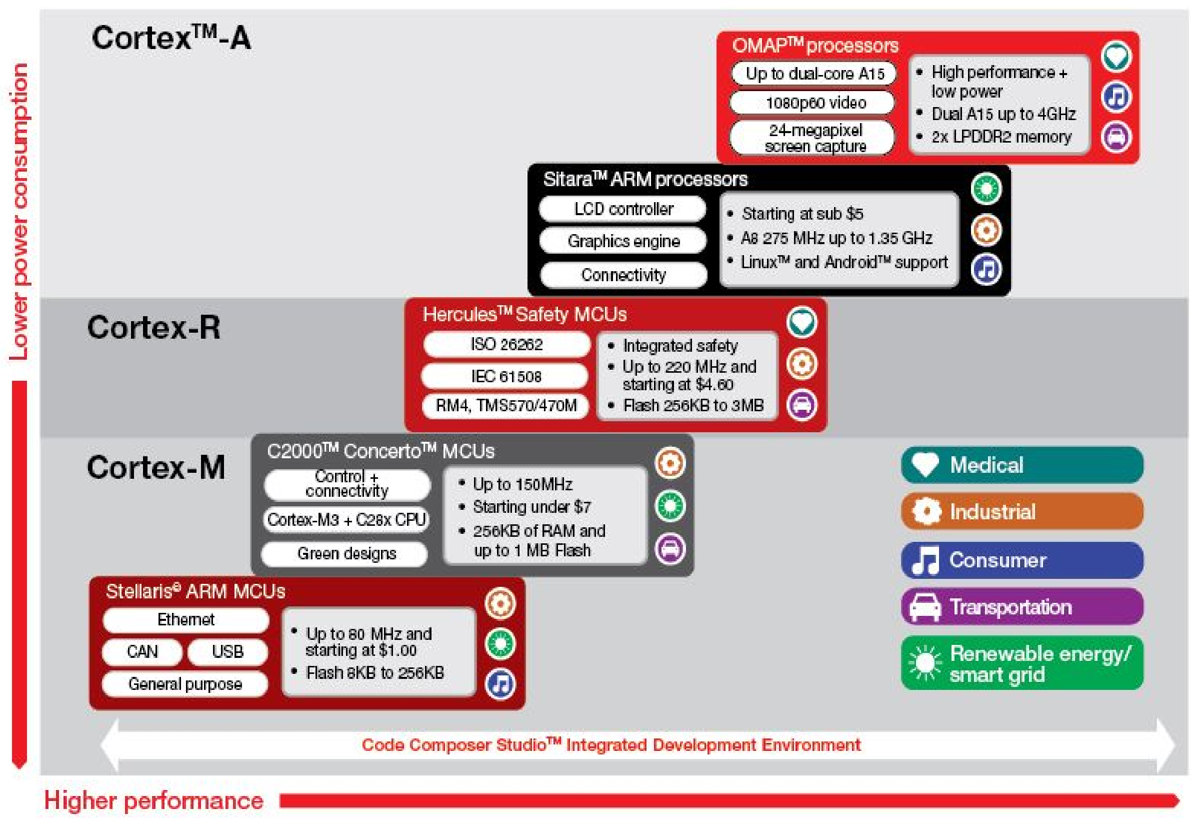
- Author's note:

  Use a Cortex-M device if you:

  - Are interested in the lowest-complexity solution for your application.
  - Can meet the needs of your application with 150 MHz or less and without a multithreaded OS running in the system.
  - Are looking for the smallest, least-expensive or lowest-power ARM device.

  If you are interested in working with a Cortex-M device from TI, visit the Stellaris® LaunchPad™ development tool website at http://www.ti.com/stellaris-launchpad.

TI's ARM-based platforms (as of August 2012) are outlined in Figure 1.



Stellaris microcontrollers. Offering performance up to 80 MHz and a high degree of connectivity and analog integration to the microcontroller markets, Stellaris MCUs are ideal for applications that require memory, analog components and communications interfaces to be on a single chip within a compact package.

Concerto™ microcontrollers. Concerto F28M35x microcontrollers combine TI's performance C28x™ core and control peripherals with an ARM Cortex-M3 core and connectivity peripherals to deliver a clearly partitioned architecture that supports real-time control and advanced connectivity in a single MCU.

Hercules™ microcontrollers. For high-reliability applications such as transportation, the TMS570 provides DSP-like performance with safety-critical features implemented in hardware to ensure continuous and uninterrupted operation. The TMS570 has a dual-core architecture, with the second core running in lockstep for redundancy and self-checking.

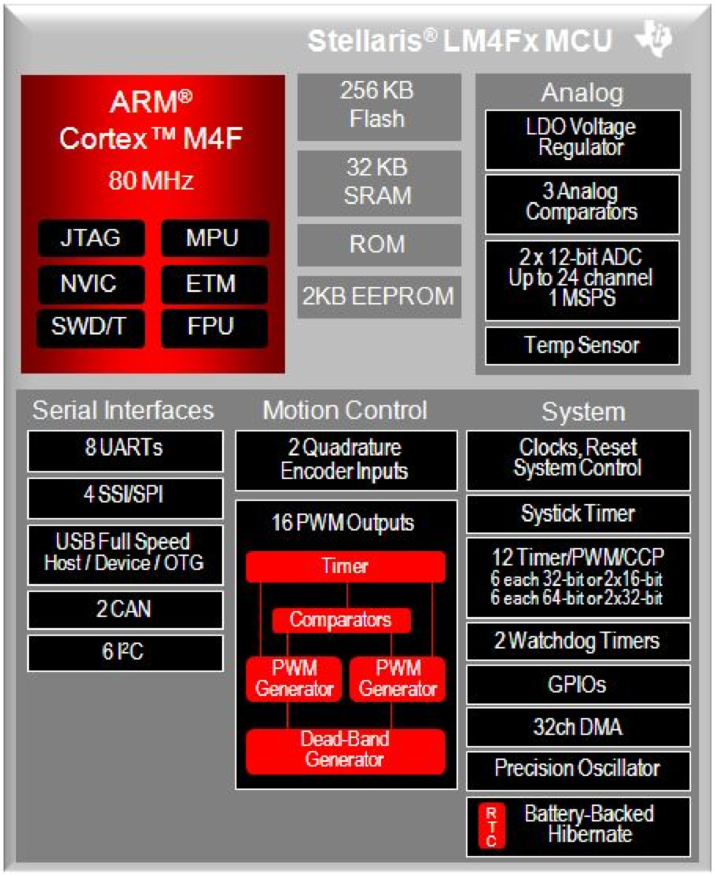
Sitara™ microprocessors. Offering performance up to 1.5 GHz, Sitara ARM MPUs are ideal for applications needing a high-level operating system, wired and wireless network connectivity, concurrent applications, and support for rich graphics with an advanced user interface.

OMAP™ multicore microprocessors. The OMAP platform for digital media processing brings together an ARM core with advanced video acceleration, plus a high-performance C6000™ DSP for applications that need to support real-time video, image and audio data processing. With the ability to provide computationally intensive real-time signal-processing performance, developers can implement complex applications such as video analytics, speech recognition, baseband channel management and power monitoring with a single chip.

Deep dive into Cortex-M – Stellaris ARM Cortex-M4F

Stellaris microcontrollers (MCUs) are 32-bit, RISC-based mixed-signal processors designed specifically for ease of use and connectivity. Common applications include end-equipment in the computing, industrial and smart grid markets.

To get a better idea of what Stellaris MCUs are and how they can be used to solve an application problem, let's take a look at a typical block diagram for the device. Figure 2 shows the block diagram for the LM4F232H5, one of the LM4F devices.



The block diagram provides guidance on the key features of a particular device. Let's take a closer look at some of the more prominent features. (Most of this section is transcribed from the LM4F232H5QC data sheet, available at [http://www.ti.com/lit/gpn/lm4f232h5qc.](http://www.ti.com/lit/gpn/lm4f232h5qc))

- Integrated memory:
    - Includes both volatile (RAM) and nonvolatile (flash, EEPROM) memories.
    - EEPROM supports an endurance of up to 500,000 writes.
    - Read-only memory (ROM) includes the software libraries used to program peripherals.

- Analog:
    - ADC: two 12-bit SAR ADCs, each with up to 12 channels of single- or dual-ended inputs.
    - Comparators: three analog comparators, each with two.
- Serial communications peripherals – both synchronous and asynchronous:
    - Two controller area network (CAN) 2.0 A/B controllers.
    - USB 2.0 controller, supporting USB On-the-Go, host and device modes.
    - Eight universal asynchronous receiver/transmitter (UART) modules, capable of infrared data (IrDA), 9-bit and ISO 7816 modes.
    - Six inter-integrated circuit (I2C) modules.
    - Four serial peripheral interface (SPI) modules.
- Motion control:
    - Two PWM modules, with a total of 16 advanced PWM outputs for motion and energy applications.
    - Eight fault inputs to promote low-latency shutdown.
    - Two quadrature encode inputs (QEIs).
- GPIOs:
    - The 64-LQFP has a maximum of 43 GPIOs; the 100-LQFP package has a maximum of 69 GPIOs; the 144-LQFP has a maximum of 105 GPIOs.
    - All pins have configurable pullup and pulldown resistors.
- Timers:
    - Systick timer – A 24-bit system timer.
    - Twelve general-purpose timers – each 32 bits, with up to two capture/compare inputs.
    - Two watchdog timers – each 32 bits.

- Hibernation module (HIB):
    - In HIB mode, power supplies are turned off to the main part of the microcontroller and only the hibernation module circuitry is active. An external wake event or RTC event is required to bring the microcontroller back to run mode.
- Oscillators:
    - Precision internal oscillator (PIOSC) – on-chip oscillator; operates at 16 MHz ±1 percent at room temperature.
    - Main oscillator (MOSC) – connection for a single-ended clock source to OSC0 or a high-frequency external crystal [5-25 MHz].
    - Hibernation module clock source – connection for a 32.758-kHz oscillator.
- CPU and debugging capabilities:
    - 80 MHz is the maximum CPU clock speed for the LM4F232.
    - Other core modules:

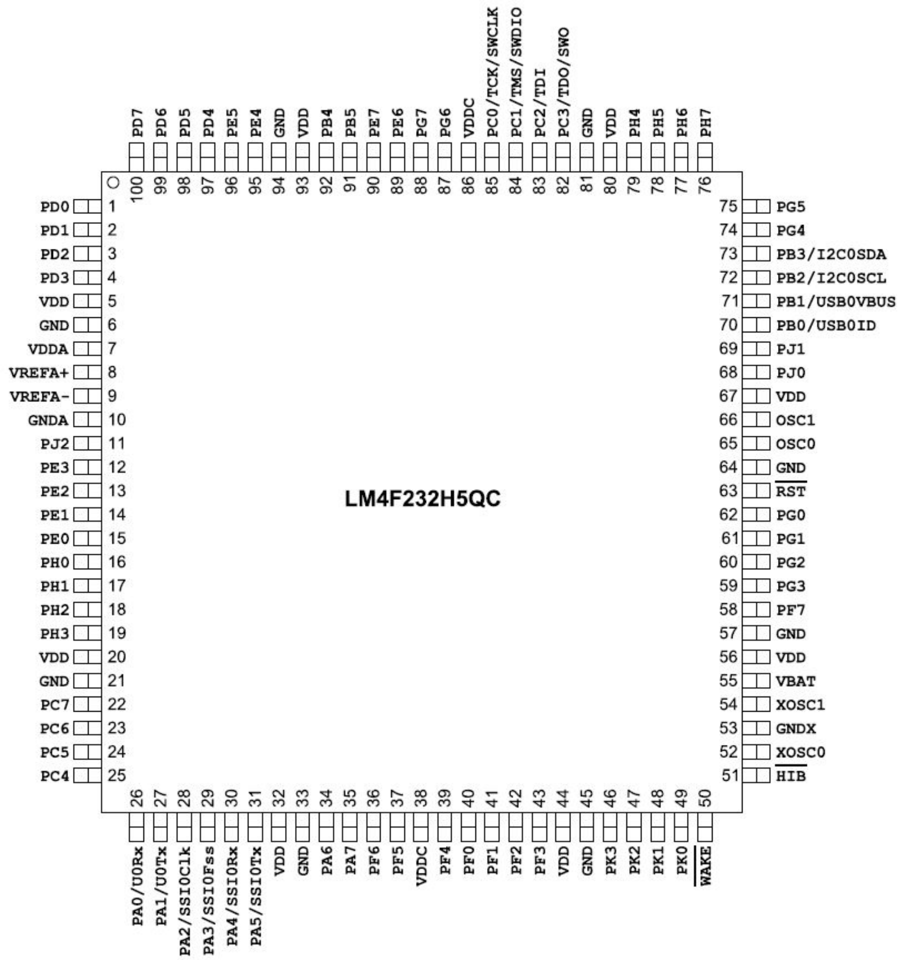
        Nested vector interrupt controller (NVIC) – provides programmable interrupt priority and low-latency interrupt handling, including automatic nesting of interrupts.
        Memory protection unit (MPU) – divides the memory map into a number of regions and defines the location, size, access permissions and memory attributes of each region.
        Floating-point unit (FPU) – supports single-precision add, subtract, multiply, divide, multiply and accumulate, and square-root operations. It also provides conversions between fixed- and floating-point data formats.

    - Debugging modules:

        Joint Test Action Group (JTAG) port – an IEEE-standard, four-pin debugging interface used to communicate with the LM4F232 during debugging.

Single-wire debugging/test (SWD/T) port – an ARM-standard two-pin debugging port, provided as an alternative to JTAG.
Embedded trace module (ETM) – a real-time trace module providing instruction and data tracing of the Cortex-M4F core.
Author's note: Leveraging the ETM requires the use of a nonstandard debugging tool as well as hardware that supports an ETM connection. Although the debugging tools exist, no hardware that supports an ETM connection is available as of September 2012. See www.ti.com/stellaris for any updates on the LM4F kits that are available.

Each of these modules is brought out through pins on a package. In the case of the LM4F232H5QC, the pin diagram is shown in Figure 3. This pin diagram can also be found in the LM4F232H5QC data sheet under the bookmark "Pin Diagram."



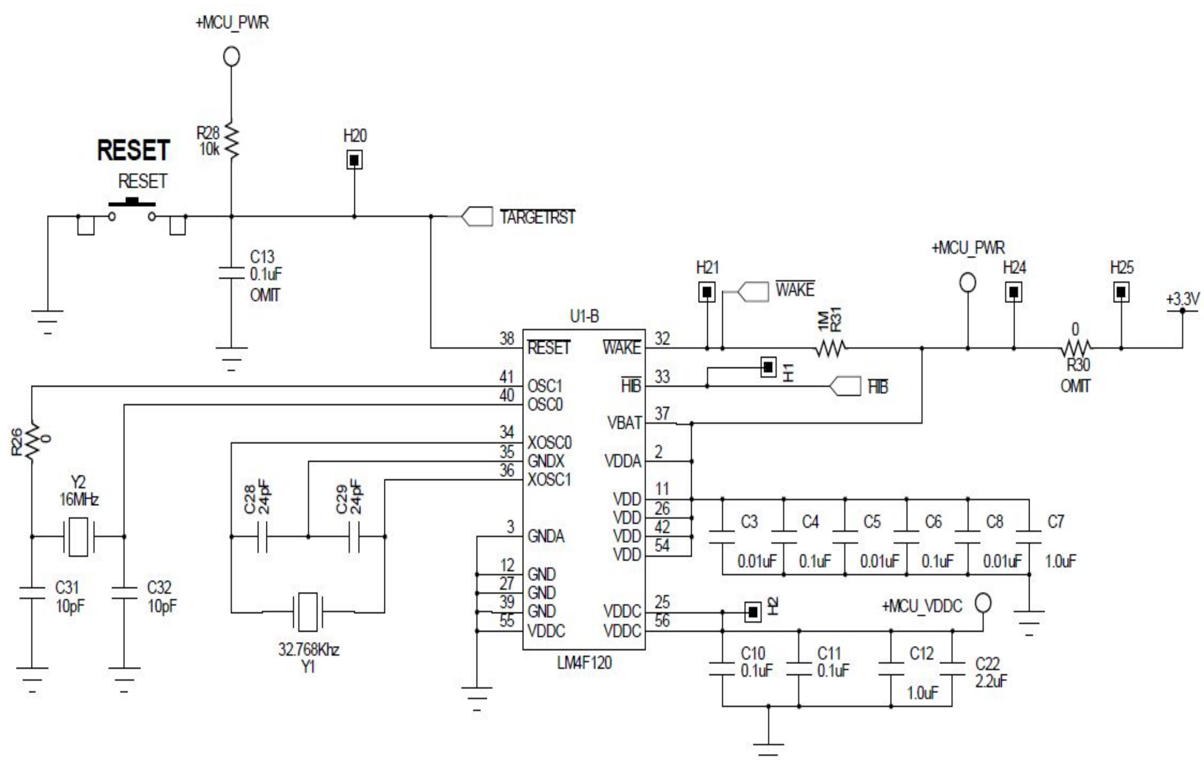
This view is helpful because it identifies the necessary connections to the LM4F232, namely the power supply (VDDx, GNDx), the programming/debugging tool connections (TCK, TMS, TDI, TDO) and some of the key peripheral connections (HIB, USB). However, many of the signals, such as the timer capture/compare pins and analog inputs, are not shown. That granularity is provided in the signal tables in the data sheet. An excerpt from the LM4F232H5QC signal tables is shown in Table 1.

I - Input
O - Output

Pin Number	Pin Name	Pin Type	Buffer Type[a]	Description
from Pin Diagram	PD0	I/O	TTL	GPIO port D bit 0.
	AIN15	I	Analog	Analog-to-digital converter input 15.
	I2C3SCL	I/O	OD	I^2C module 3 clock. Note that this signal has an active pull-up. The corresponding port pin should not be configured as open drain.
1	M0PWM6	O	TTL	Motion Control Module 0 PWM 6. This signal is controlled by Module 0 PWM Generator 3.
Alternate Pin Functions	M1PWM0	O	TTL	Motion Control Module 1 PWM 0. This signal is controlled by Module 1 PWM Generator 0.
	SSI1Clk	I/O	TTL	SSI module 1 clock
	SSI3Clk	I/O	TTL	SSI module 3 clock
	WT2CCP0	I/O	TTL	32/64-Bit Wide Timer 2 Capture/Compare/PWM 0.

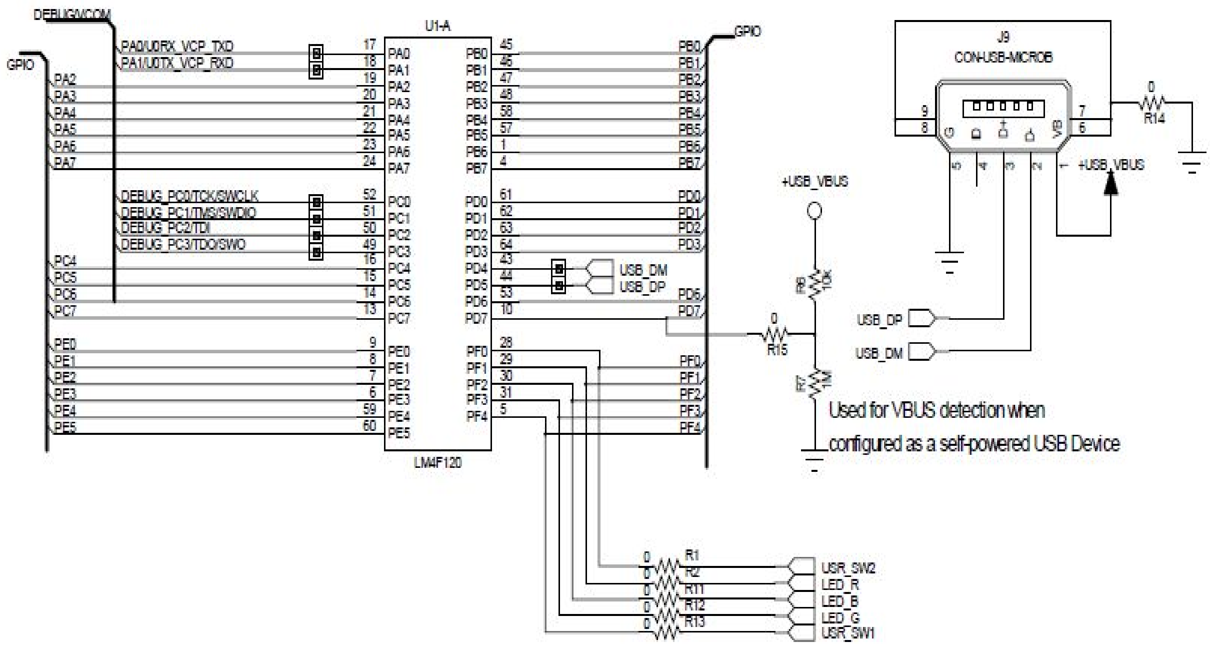
Table 1. Exerpt from the LM4F232H5QC data sheet showing showing part of the signal table.

Using these tables, you can start to map the desired functionality to your design. Figure 4 is a schematic drawing depicting the baseline connections for an LM4F120 design. The LM4F120 and the LM4F232 are actually members of the same device family, so the schematic applies to the part under discussion.



Since the LM4F power rail is specified as 3.3 V ± 5 percent, a typical 3.3-V supply will work well. Note the decoupling capacitors on the VDD pins. Signals like WAKE and RESET are connected to user switches that are configured as pullups. A 16-MHz oscillator and 32-kHz oscillator are connected to the MOSC and HIBOSC pins, respectively.

Figure 5 goes one step further to demonstrate an example connection to the debugging, USB and user interface signals.



Note the connections to the USB connector and the JTAG signals. Since this is a schematic from the [Stellairs LaunchPad](#) evaluation kit, this also includes the connections to a virtual COM port bus that uses UART on Port A pins 0 and 1 to communicate back to the debugging emulator. The schematic also includes the breakout to the pin headers. These other pin connections can be used to connect all other signals.

Now that we have explained the basics of how to include an LM4F device in your system, let’s review the documents you can use to take your design to the next level.

- Device-specific data sheet (example: [LM4F232H5QC data sheet:](#))

The data sheet includes detailed descriptions of the modules, register descriptions, maximum operating conditions, electrical parameters, performance boundaries and package descriptions for each device. Each part number has its own data sheet.

- Device-specific errata (example: LM4F232H5QC errata:)

The errata document is a critical supplement to the data sheet because it lists any bugs that affect the operation of the device, as well as any workarounds. Note that errata vary by revision, so it is important to map the revision of your device to the correct errata document.

Data sheet deep dive
Beyond the pin diagram and signal tables, let's highlight some other areas you should focus on when you first look at the data sheet.

Boundary and recommended operating conditions

- Maximum ratings and recommended operating conditions (Table 2):

Characteristic	Symbol	Value	Unit
Industrial operating temperature range	T_A	-40 to +85	°C
Unpowered storage temperature range	T_S	-65 to +150	°C

Table 2. Table from data sheet showing reccomended operating conditions.

The maximum ratings indicate the voltage and current conditions that should not be exceeded, under any condition, without risking damage to the device (Table 3). The recommended operating conditions document the conditions under which the part is guaranteed to operate (Table 4). The minimum and maximum electrical specifications in the data sheet are specified under these conditions.

Parameter	Parameter Name[a]	Value		Unit
		Min	Max	
V_{DD}	V_{DD} supply voltage	0	4	V
V_{DDA}	V_{DDA} supply voltage	0	4	V
V_{BAT}	V_{BAT} battery supply voltage	0	4	V
V_{IN_GPIO}	Input voltage on GPIOs, regardless of whether the microcontroller is powered[bc]	-0.3	5.5	V
	Input voltage for `PB0` and `PB1` when configured as GPIO	-0.3	V_{DD} + 0.3	V
$I_{GPIOMAX}$	Maximum current per output pin	-	25	mA

Table 3. Table in data sheet showing maximum ratings.

Parameter	Parameter Name	Min	Nom	Max	Unit
V_{DD}	V_{DD} supply voltage	2.97	3.3	3.63	V
V_{DDA}	V_{DDA} supply voltage	2.97	3.3	3.63	V
V_{DDC}	V_{DDC} supply voltage	1.08	1.2	1.32	V

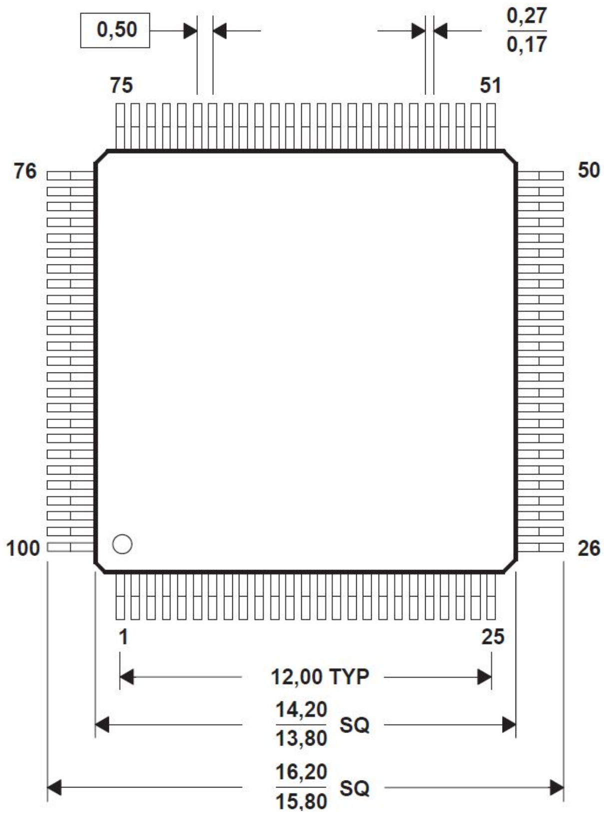
Table 4. Recommended operating conditions table from a data sheet.

Power consumption numbers (Table 5):

Parameter	Parameter Name	Conditions	Nom	Max	Unit
I_{DD_RUN}	Run mode 1 (Flash loop)	V_{DD} = 3.3 V V_{DDA} = 3.3 V Peripherals = All ON System Clock = 80 MHz (with PLL) Temp = 25°C	50	-	mA
	Run mode 1 (SRAM loop)	V_{DD} = 3.3 V V_{DDA} = 3.3 V Peripherals = All ON System Clock = 80 MHz (with PLL) Temp = 25°C	40	-	mA
	Run mode 2 (Flash loop)	V_{DD} = 3.3 V V_{DDA} = 3.3 V Peripherals = All OFF System Clock = 80 MHz (with PLL) Temp = 25°C	30	-	mA
	Run mode 2 (SRAM loop)	V_{DD} = 3.3 V V_{DDA} = 3.3 V Peripherals = All OFF System Clock = 80 MHz (with PLL) Temp = 25°C	20	-	mA

Table 5. Power consumption data table from a data sheet.

- Package information that includes package tolerances is useful when creating device footprints in schematic/PCB CAD tools (Figure 6):

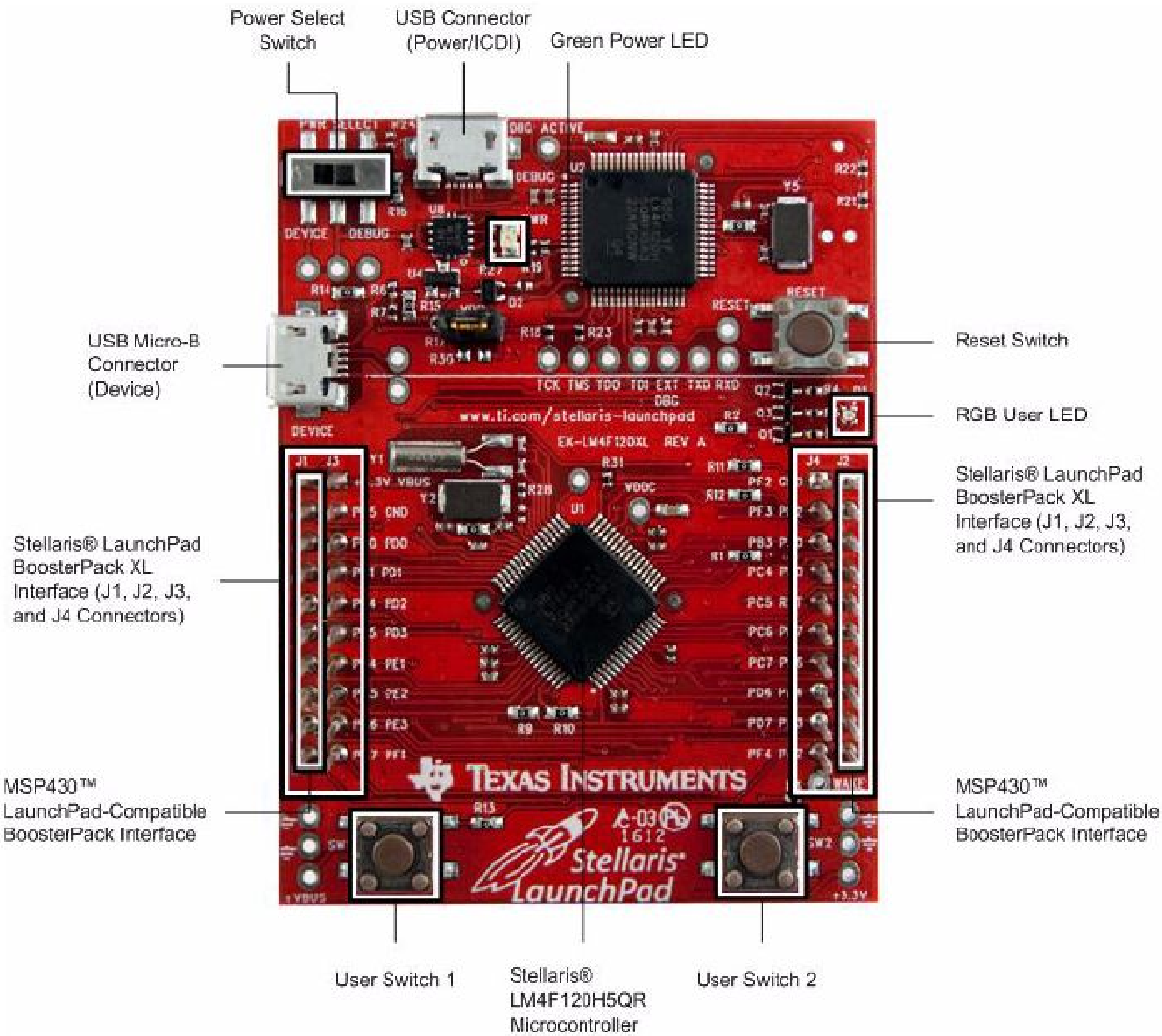


To select your part, please refer to the series of questions and answers near the end of Section 2.2, "Overview of the MSP430 microcontroller from Texas Instruments," that begins with the question, "What problem am I trying to solve?" You can walk through this process for Stellaris processors just as you can for MSP430 microcontrollers.

There are a variety of LM4F devices that will fit a variety of different needs. Sometimes the easiest way to see whether a device is the right one for your application is to get your hands on an evaluation module. In the case of the LM4F232 family, the Stellaris LaunchPad development tool is the recommended kit.

The Stellaris LaunchPad evaluation kit costs less than $10 and provides a variety of booster packs to extend its functionality (Figure 7). See

www.ti.com/stellaris to start your design today.



Discrete Components
This module is written to help students doing their senior project design chose the needed discrete components. It will include some tips about designing with discrete components along with giving a list of ones that will most likely fulfill their needs.

Discrete components

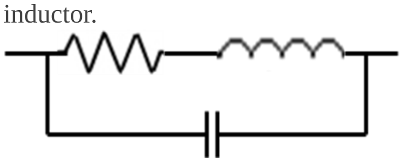
It is almost impossible to complete a circuit design without including discrete components. Most instruction at university courses about these devices focus on the theory of their operation. You will learn about Ohm’s law and all of the theory that ties the law to resistors, capacitors and inductors. You’ll learn transistor theory and all of the aspects that it includes. And as I remember, the concepts of a diode seem to have fallen into the same discussion.

This section will be split into two subsections:

- Passive components.
- Active components.

Passive components

Passive components are resistors, capacitors and inductors. The surprise that most circuit designers encounter when first using passive components can be shown in Figure 1: the circuit equivalent for a resistor, capacitor or inductor.



The equivalent circuit for a resistor, capacitor or inductor.

Put into words, every resistor has an element of inductance and capacitance. Every capacitor has an element of resistance and inductance. And every inductor has an element of resistance and capacitance. In each case, their influence on the actual value of the component will be a function of the frequency of the signal applied to the device.

Here are a couple of examples to get you thinking:

- A wire-wound resistor has an element of inductance that may significantly alter the performance of the resistor over the frequency range of the circuit design.
- In a power supply, a small ceramic capacitor may be required to eliminate the high frequencies passed by the larger electrolytic capacitor due to its significantly lower inductance component as a result of how it is made.
- An inductor that has been made by winding wire around a core will have the DC resistance component of that wire.

Active components

I’ll cover two basic types of active components: diodes and transistors. A diode in its most simple application allows current to flow in only one direction. A transistor in its most simple application can act as a signal amplifier or as a switch.

Since both of these active elements can be easily integrated onto a silicon substrate, they are the workhorses found in all integrated circuits available today, both analog and digital. The only time you will need to use discrete diodes and transistors is when you need to do something that is considered beyond the capability of an IC. (Generally, what is considered beyond the capability of an IC is too high of a voltage on the device or too high of a current flowing through the device.)

In each of the discussions on these discrete components, I will assume that you already understand the theory behind them and are looking for some basic ideas on how to use them in your senior project design.

Resistors

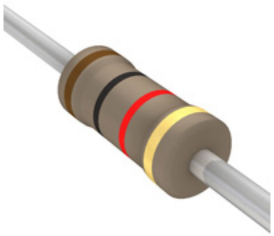
Resistors are typically the easiest discrete components to understand and use. They can be found in all sorts of sizes and configurations. Rather than have an exhaustive discussion on resistors, let's just do a quick overview.

The film resistor is probably the easiest-to-recognize form of a resistor. Besides having to know the color code for determining the value of the resistor, it is also important to know the tolerance and wattage.

Color code

There are several ways to remember the color code. The mnemonic I used to learn it many years ago is not politically correct, so I will not use it here as an example. But you can find several on the Web or from a professor that can help you learn the color code.

So the first three colors for a 1K-ohm resistor would be brown, black and red. Figure 2 is a 1K ohm, ¼ watt, 5 percent resistor.



A 1K ohm, 1/4 watt, 5 percent resistor.

Notice that the fourth band in the picture is gold, which means it has a 5 percent tolerance.

Tolerance

Most resistors found in a lab have a 5 percent tolerance. This means that a 1K-ohm resistor could vary anywhere from 950 to 1,050 ohms. An interesting observation is that the 5 percent resistor series is set up such that two adjacent resistor values are within 10 percent of each other. That means that a resistor, once manufactured, will always fit into one of the tolerances.

In practical terms, the two resistor values adjacent to the 1-K resistor are the 910 ohm and 1.1-K ohm. Expressed as in Table 1, you can see how this works.

Nominal	-5%	+5%	Overlap	Color code
910	865	955	5	W, Br, Br
1 K	950	1,050		Br, Bl, R

Nominal	**-5%**	**+5%**	**Overlap**	**Color code**
1.1 K	1,045	1,155	5	Br, Br, R

Example of the overlap between 5 percent tolerance resistors.

The 910-ohm resistor could be as much as 955 ohms on the high side of its allowable tolerance and the 1K-ohm resistor could be as little as 950 ohms on the low side of its allowable tolerance, giving a 5-ohm overlap.

Knowing this piece of information can help when picking out the next-size-larger resistor. But in case you don't want to do this exercise, below is a chart with the values for a 5 percent tolerance resistor. Notice that it also includes a chart for 10 percent tolerance capacitors.

Standard Resistor Values (±5%)						
1.0	10	100	1.0K	10K	100K	1.0M
1.1	11	110	1.1K	11K	110K	1.1M
1.2	12	120	1.2K	12K	120K	1.2M
1.3	13	130	1.3K	13K	130K	1.3M
1.5	15	150	1.5K	15K	150K	1.5M
1.6	16	160	1.6K	16K	160K	1.6M
1.8	18	180	1.8K	18K	180K	1.8M
2.0	20	200	2.0K	20K	200K	2.0M
2.2	22	220	2.2K	22K	220K	2.2M
2.4	24	240	2.4K	24K	240K	2.4M
2.7	27	270	2.7K	27K	270K	2.7M
3.0	30	300	3.0K	30K	300K	3.0M
3.3	33	330	3.3K	33K	330K	3.3M
3.6	36	360	3.6K	36K	360K	3.6M
3.9	39	390	3.9K	39K	390K	3.9M
4.3	43	430	4.3K	43K	430K	4.3M
4.7	47	470	4.7K	47K	470K	4.7M
5.1	51	510	5.1K	51K	510K	5.1M
5.6	56	560	5.6K	56K	560K	5.6M
6.2	62	620	6.2K	62K	620K	6.2M
6.8	68	680	6.8K	68K	680K	6.8M
7.5	75	750	7.5K	75K	750K	7.5M
8.2	82	820	8.2K	82K	820K	8.2M
9.1	91	910	9.1K	91K	910K	9.1M

Standard Capacitor Values (±10%)						
10pF	100pF	1000pF	.010µF	.10µF	1.0µF	10µF
12pF	120pF	1200pF	.012µF	.12µF	1.2µF	
15pF	150pF	1500pF	.015µF	.15µF	1.5µF	
18pF	180pF	1800pF	.018µF	.18µF	1.8µF	
22pF	220pF	2200pF	.022µF	.22µF	2.2µF	22µF
27pF	270pF	2700pF	.027µF	.27µF	2.7µF	
33pF	330pF	3300pF	.033µF	.33µF	3.3µF	33µF
39pF	390pF	3900pF	.039µF	.39µF	3.9µF	
47pF	470pF	4700pF	.047µF	.47µF	4.7µF	47uF
56pF	560pF	5600pF	.056µF	.56µF	5.6µF	
68pF	680pF	6800pF	.068µF	.68µF	6.8µF	
82pF	820pF	8200pF	.082µF	.82µF	8.2µF	

A tighter tolerance resistor might be wire-wound in order to guarantee its tolerance. But due to the nature of its manufacture, it may tend to have an inductive component at higher frequencies. So when picking a resistor for the circuit, keep this in mind. I'll discuss this issue further in the Capacitors section.

Wattage

One mistake you should try to avoid in circuit design is using a resistor that is not capable of handling the power dissipation it must handle. It is easy to assume that a ¼ watt resistor can handle ¼ of a watt. But this is incorrect on two counts: failing to determine the power dissipation of the resistor in the active circuit, and assuming that a ¼ watt resistor will handle a ¼ watt load.

You'd realize the first error relatively fast, once you'd turned on the power. The resistor in question would become warm to the touch, then get really hot to the touch, begin to smoke or blow up. All of these conditions indicate that you need a larger-wattage resistor. To determine the power through a resistor, it is best to use Ohm's law (Equation 1) to determine the power:

E = I x R

Power = E x I = E^2/R = (I^2) x R

You can avoid the second error by applying a good engineering practice: always double the calculated (or measured) power by 2 to get the wattage for the resistor. Simply stated, a ¼ watt resistor should never see more than ⅛ of a watt of power through it.

Picking a resistor

Resistors are usually commonly stocked in the lab. In many cases, they are typical ¼ watt, 5 percent carbon film resistors. This is where the color-code chart becomes handy: to make sure you actually have the resistors you need. Your lab may also have surface-mounted resistors. These are great to use when you need a smaller footprint for the resistor and you have the tools to properly attach them to the printed circuit board.

Color-code chart

Figure 3 Shows a typical resistor color-code chart.

Color	Value	Multiplier	Tolerance
Black	0	$\times 10^{0}$	± 20%
Brown	1	$\times 10^{1}$	± 1%
Red	2	$\times 10^{2}$	± 2%
Orange	3	$\times 10^{3}$	± 3%
Yellow	4	$\times 10^{4}$	- 0, + 100%
Green	5	$\times 10^{5}$	± 0.5%
Blue	6	$\times 10^{6}$	± 0.25%
Violet	7	$\times 10^{7}$	± 0.10%
Gray	8	$\times 10^{8}$	± 0.05%
White	9	$\times 10^{9}$	± 10%
Gold	–	$\times 10^{-1}$	± 5%
Silver	–	$\times 10^{-2}$	± 10%
None	–	–	± 20%

Resistor color code chart.

There are many others available if this one doesn’t suit you. You can find more charts here: [https://www.google.com/search?q=resistor+color+code+chart&hl=en&tbo=u&tbm=isch&source=univ&sa=X&ei=2XvwUJ_RDcjm2AW084GwDA&ved=0CC4QsAQ&biw=1680&bih=890.](https://www.google.com/search?q=resistor+color+code+chart&hl=en&tbo=u&tbm=isch&source=univ&sa=X&ei=2XvwUJ_RDcjm2AW084GwDA&ved=0CC4QsAQ&biw=1680&bih=890)

Digi-Key part numbers

Obtaining resistors for your project should be relatively easy. They are usually stocked in the lab. But if they are not, there is a quick way to order them from Digi-Key while you are ordering other parts.

The part number you will need for any ¼ watt resistor from Digi-Key is put in an easy format. The 1-ohm through 9.1-ohm resistors have part numbers with the form of 1.0QBK-ND through 9.1QBK-ND. The 10-ohm through 91-ohm resistors have part numbers with the form 10QBK-ND through 91QBK-ND. Table 2 lists the general forms for each decade:

Ohm value	Digi-Key part No.
1	1.0QBK-ND

Ohm value	Digi-Key part No.
10	10QBK-ND
100	100QBK-ND
1 K	1.0KQBK-ND
10 K	10KQBK-ND
100 K	100KQBK-ND
1 M	1.0MQBK-ND
10 M	10MQBK-ND

Generic form for Digi-Key part numbers of 1/4 watt resistors.

Capacitors

There are many capacitors to choose from; that makes it easy to get thoroughly confused when trying to select them. To keep our discussion relatively straightforward, I will describe only a few of the more popular versions.

First, capacitors come in many shapes and sizes, such as:

- Ceramic.
- Electrolytic.
- Tantalum.

They are also used in many different applications, such as:

- Power supplies.
- Bypass capacitors.
- Simple oscillators.

For the purposes of your senior project, these parameters should be adequate. I will assume that you know the theory necessary to be able to use them in a circuit.

This discussion will focus on the real-world use of capacitors in a circuit, or at least the ones you will most likely face while designing your senior project.

Shapes

It is generally easy to determine the type of capacitor by its shape. The two most common shapes are a cylindrical device with two leads, either on each end or both out the same end. In most cases, there will be markings to let you know which side is the positive side and which is the negative side. It is important that you make the positive and negative connections properly or the capacitor could blow up.

Electrolytic and tantalum capacitors are made in this shape. They also tend to have large capacitive values. I generally think of them in the 10-µF to 500-µF range, although they are available in ranges both below and above this. These capacitors are often used as storage elements, or perhaps in a power supply.

Another shape is a flat shape that looks a bit like a coin with two wires sticking out of its edge. These capacitors are usually used for signals in a circuit. Their capacitive values are in the pF range to units of µFs. And of course, they can go beyond this range.

Finally, there are surface-mount capacitors. Unlike the previous two shapes, these do not have leads on them. Rather than having leads that go through holes in the printed circuit board, these are mounted on the surface of the printed circuit board.

Uses

For the purposes of this discussion, I'll limit the list of uses for a capacitor to:

- A storage element.
- A filter element.
- A timer element.

Virtually every power supply has some sort of a storage element on its output to make sure that there is enough energy stored to handle variations in current demand while keeping a relatively constant voltage. Typically, a large electrolytic capacitor is used to give the necessary buffering.

In many DC-to-DC converters, a toroid-based transformer allows a higher frequency through the transformer (many simple power supplies use 50 or 60 Hz from the power grid), giving higher efficiencies. But, it also has frequency components on the output of the DC-to-DC converter that are difficult for a large electrolytic capacitor to filter out; this is a result of the significant inductance component found in the capacitor. In these cases, a ceramic capacitor is placed in parallel with the larger electrolytic. Given its construction, the ceramic capacitor has very little inductance and therefore can filter out the higher frequencies that the larger electrolytic capacitor does not see.

To extend this idea, ceramic capacitors work well with resistors (and inductors) to create filter elements. Adding active components such as transistors or operational amplifiers can perform significant filtering of a signal.

Finally, you can use capacitors along with resistors to create timing elements and clock generators. Once again, this is best accomplished with the inclusion of active components.

Picking a part

Table 3 is a chart to help you pick the best part for your design. I have included the Digi-Key part number for each to make it easy for you to order the right part.

Type	**Farads**	**Voltage**	**Digi-Key part No.**
Electrolytic			
	10 µF	250 V	565-1201-ND
	100 µF	250 V	565-1397-ND
	200 µF	16 V	NLW200-16-ND
	500 µF	16 V	WBR500-16A-ND
Ceramic			
	0.001 µF	50 V	490-3814-ND
	0.01 µF	50 V	490-5396-ND

Type	Farads	Voltage	Digi-Key part No.
	0.1 µF	50 V	490-5401-ND
Surface-mount			
	1.0 µF	50 V	445-4576-1-ND
	2.2 µF	10 V	445-7712-1-ND
	4.7 µF	10 V	445-4056-1-ND
	10 µF	50 V	445-5999-1-ND
	22 µF	25 V	445-6000-1-ND
	47 µF	25 V	445-8047-1-ND
	100 µF	10 V	445-6007-1-ND

Selected Capacitors with their Digi-Key part numbers.

Inductors

Inductors are probably the least used of the passive components – or at least it seems that way. The reasoning for their somewhat rare use is the difficulty in integrating an inductor onto a silicon substrate. With the advent of digital filters, you can easily do most of the signal filtering in the digital domain. But that is far too narrow of a view of how inductors are used.

I won't discuss any theory in this section, as there are many references you can use to learn about inductors [1].

Table 4 is a quick reference guide to pick the best inductor for your design.

Size	Current	Digi-Key part No.
220 nF	1.15 A	M10148-ND
1 µF	815 mA	M10137-ND
1.8 µF	655 mA	78F1R8K-RC-ND
2.2 µF	630 mA	M10140-ND
4.7 µF	1.28 A	M8277-ND
10 µF	180 mA	M8181-ND
15 µF	205 mA	M8183-ND
22 µF	190 mA	M10101-ND

Size	Current	Digi-Key part No.
33 µF	240 mA	M10111-ND
47 µF	195 mA	M10119-ND
100 µF	160 mA	M10082-ND
150 µF	140 mA	M10093-ND
220 µF	125 mA	M10102-ND
470 µF	92 mA	M10120-ND
1 mH	70 mA	M10083-ND
2.2 mH	50 mA	M10103-ND
4.7 mH	31 mA	M10121-ND
10 mH	24 mA	M10084-ND
47 mH	13 mA	M10122-ND
100 mH	65 mA	M8337-ND

Selected Inductors with their Digi-Key part numbers.

A diode is a two-terminal electronic component with an asymmetric transfer characteristic, with low (ideally zero) resistance to current flow in one direction and high (ideally infinite) resistance in the other. A semiconductor diode (the most common type today) is a crystalline piece of semiconductor material with a p-n junction connected to two electrical terminals [2].

Diodes have many uses in a circuit design, but let's focus on the most likely ones you'll be faced with in your senior project design. Those uses are:

- Power supplies.
- Signals.
- LED lighting.

But before getting to its uses, I'll first give you a bit of background on the diode.

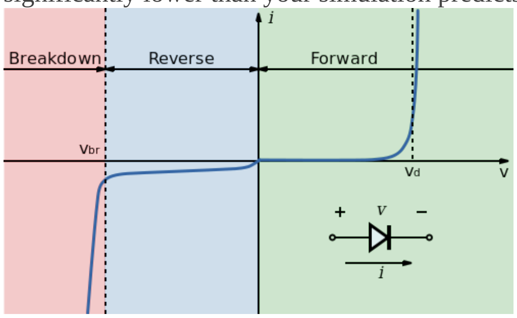
Background

As you should remember, the basic concept of a diode is to allow current to flow in only one direction. This is correct until enough voltage applied to the diode in the reverse direction exceeds the reversed breakdown voltage (Vbr). It is important when choosing a diode to make sure that its Vbr is significantly larger than the signal voltage it will be seeing.

But there are cases where you can use the Vbr to your advantage. Zener diodes use this voltage to regulate an output voltage in a simple power-supply circuit. The Zener diode is used to create a reference voltage for the power-supply output. The Zener diode will be discussed a bit further later in this section.

As you can see in Figure 4, there is a forward voltage drop (Vd) of about 0.7 V. This is important to keep in mind, particularly if the signal being acted on is about the same as (or less than) the Vd.

Finally, when using diodes in a high-frequency circuit, such as blocking a high-frequency signal or rectifying an AC voltage, make sure that you pay attention to the reverse recovery time of the diode. This is a result of the amount of time before the diode can block current flow in the reverse direction. If ignored, you may realize that a diode looks just like a piece of bus wire at high frequencies, or that the efficiency of your power supply is significantly lower than your simulation predicts.



Diode's voltage and current curve.

With that brief background, let’s discuss the various uses of a diode.

Power supplies

Power supplies use diodes in several different ways. The first way is to rectify an AC voltage, resulting in a DC voltage. A typical circuit will have four diodes in the form of a bridge, allowing both halves of the sine wave to be converted to a pulse-shaped DC voltage. A large capacitor is put across the output signal to smooth the pulses into a constant DC voltage. Some sort of voltage regulator circuit is included to help maintain the correct DC voltage.

The diodes used in this way are power diodes, and the capacitor is usually an electrolytic or tantalum capacitor in the range of 10 to 200 µF (maybe more or less, depending on the variability and size of the load).

A second use of a diode in a power supply is to create a voltage reference. The type of diode used for this is a Zener diode. In its simplest form, the Zener diode controls the output voltage of a series pass transistor. Zener diodes generally run from about 2 V to about 200 V.

Remember that if you need a voltage reference below 2 V, using one or two signal diodes in series can be used for 0.7 V and 1.4 V, respectively. It is important on a Zener to stay within the power dissipation specification. The power can be estimated by multiplying the Zener voltage by the current load on the diode.

It is good to revisit the concept of reverse recovery time. When the AC voltage source is 50/60 Hz, a power diode generally works fine. (I first designed with a 1N4001.) But as this frequency goes up in a DC-to-DC converter, the reverse recovery time of the diodes in the rectifier bridge becomes a significant component in determining power efficiency. Depending on the power requirements of the overall circuit, a signal diode may be a better choice for the bridge.

Signals

Diodes can be used to alter the shape of a signal. They can clip a signal such that only the positive (or negative) part of the signal passes. This could be valuable when trying to capture a pulse riding on a large DC component.

Lighting

The term lighting is probably an understatement of what a diode can do in terms of creating light or capturing light. Light-emitting diodes (LEDs) have been used for years as indicator lights or display elements. They come in various colors and brightness. A whole new industry is happening using LEDs to replace conventional lights in our consumer and commercial applications.

Picking a diode for your design

Table 5 is a simple chart to give you a start on picking a diode for your design. It is separated into uses, with a couple of specifications that you need to consider. Included are a few of the key parameters for the devices.

Use	**Part no.**	**Fwd V (Vf)**	**Rev V (Vr)**	**Rev (trr)**	**Current (lo)**	**Digi-Key part No.**
Pwr						
	1N4001	1.1 V@1 A	50 V	500 nS	1 A	1N4001GOS-ND
	1N4002	1.1 V@1 A	100 V	500 nS	1 A	1N4002GOS-ND
	1N4003	1.1 V@1 A	200 V	500 nS	1 A	1N4003GOS-ND
	1N4004	1.1 V@1 A	400 V	500 nS	1 A	1N4004GOS-ND
	1N4005	1.1 V@1 A	600 V	500 nS	1 A	1N4005GOS-ND
	1N4006	1.1 V@1 A	800 V	500 nS	1 A	1N4006GOS-ND
	1N4007	1.1 V@1 A	1,000 V	500 nS	1 A	1N4007GOS-ND
Small sgnl						
	1N914	1.0 V@10 mA	75 V	4 nS	200 mA	1N914BCT-ND
	1N916	1.0 V@20 mA	100 V	4 nS	200 mA	1N916AFS-ND
Zener						
	Part no.	**Volt (Vz)**	**Pwr (max)**			**Digi-Key part No.**
	1N4747	20 V	1 W			1N4747AFSCT-ND
	1N4748	22 V	1 W			1N4748AFSCT-ND
	1N4746	18 V	1 W			1N4746AFSCT-ND
	1N4749	24 V	1 W			1N4749AFSCT-ND
	1N4752	33 V	1 W			1N4752AFSCT-ND
	1N4750	27 V	1 W			1N4750AFSCT-ND

Use	Part no.	Fwd V (Vf)	Rev V (Vr)	Rev (trr)	Current (lo)	Digi-Key part No.
	1N5349	12 V	5 W			1N5349BRLGOSCT-ND
	1N5337	4.7 V	5 W			1N5337BRLGOSCT-ND
	1N5344	8.2 V	5 W			1N5344BRLGOSCT-ND
	1N5352	15 V	5 W			1N5352BRLGOSCT-ND
	1N5333	3.3 V	5 W			1N5333BRLGOSCT-ND

Selected diodes with their Digi-Key part numbers.

Transistors

A transistor is a semiconductor device used to amplify and switch electronic signals and electrical power. It is made up of semiconductor material, with at least three terminals for connection to an external circuit.

A voltage or current applied to one pair of the transistor's terminals changes the current flowing through another pair of terminals. Because the controlled (output) power can be higher than the controlling (input) power, a transistor can amplify a signal. Today, some transistors are packaged individually, but many more are found embedded in integrated circuits [3].

Once again, I will leave theory out of this discussion, as you should already have learned it or can find many good sources with which to refresh your memory. With that said, let’s discuss how to pick the best transistor for your design.

Picking the right transistor

It is easy to get overwhelmed when picking the best transistor for your design. Table 6 is a quick chart to match your need to a device.

Use	Part No.	Type	hFE	Ic	Ft	Pwr (max)	Digi-Key part N
General purpose							
	2N2222	NPN	100	600mA	300MHz	625mW	P2N2222AGOS-ND
	2SC4083T106N	NPN	56	50m A	3.2GHz	200mW	2SC4083T106N ND

Use	Part No.	Type	hFE	Ic	Ft	Pwr (max)	Digi-Key part N
	2SC4083T106P	NPN	82	50m A	3.2GHz	200mW	2SC4083T106P(ND
	2N3904	NPN	100	200mA	300MHz	625mW	2N3904TFCT-N
	2N3906	PNP	100	200mA	250MHz	625mW	2N3906D26ZCT ND

Selected transistors with their Digi-Key part numbers.

References

1. http://en.wikipedia.org/wiki/Inductor
2. http://en.wikipedia.org/wiki/Diode
3. http://en.wikipedia.org/wiki/Transistor

The Engibous Prize
This module introduces the Engibous Prize which is sponsored by Texas Instruments. It presents an overview of the contest. Then introduces Tom Engibous, of whom the Prize is named after. Finally it presents the rules of the contest.

The Engibous Prize

One of the most valuable experiences you will have in your undergraduate education is working in teams. The first chapter of this book covered the importance of this experience and the lessons you should learn from it. We at TI believe that this is so important that we created a design contest to give you an opportunity to show off what you have learned to your classmates at your university and also those at other universities. We named the prize after our retired CEO, Tom Engibous.

To enter the contest, sign up on our analog design contest Web page at http://www.ti.com/corp/docs/landing/universityprogram/enter.htm. The site also includes the rules and a list of previous winners.

Judging happens in three phases. First, we identify one or two teams from a university with more than three entries (based on eligibility to the contest and quality of project). These teams advance to the next level. Second, we identify the top teams and invite them to the Engibous Summit. The Engibous Summit is held at TI’s headquarters in Dallas, Texas, and comprises several events where students and professors mingle with TI executives, including award ceremonies. A panel of judges selects the top three teams.

The first-place team receives a $10,000 prize. The second-place team receives $7,500 and the third-place team receives $5,000. One additional team from the final 12 teams is recognized as the "People’s Choice" based on voting from those visiting the poster session during the Engibous Summit.

So that's a quick summary of the contest. Now here are a few hints on how to prepare your entry for the Engibous Prize. Then I'll introduce Tom Engibous, for whom the prize is named, and get to the rules.

Hints to create a good entry

Here's how best to prepare your entry for the Engibous Prize with the information that the judges will want to see. These hints are not necessarily in order of importance:

- We prefer that you write your entry in prose. We are comfortable with either a Word document or a PDF. If your university requires that you complete the project with a slide presentation, we will accept it, although it is not our preference.
- Please keep your paper length to about 25 pages (20 to 30). If you want to include more detail such as program listings, parts lists, etc., put that into an appendix.
- Make sure that you list the TI components you used in your project such that it is easy for the judges to find. Although it is not required, the more TI devices you use, the happier the judges will be when they evaluate your project.
- We expect the project to actually work. But do not interpret this expectation too literally. If you feel you have accomplished the goal of your project, say so. Don’t let us guess.

Enough hints; now allow me to introduce Tom Engibous.

Tom Engibous

Thomas (Tom) Engibous (pictured in Figure 1) is the retired chairman of Texas Instruments, one of the world’s leading electronics companies. He was also a member of the TI board of directors from 1996 to 2008. Previously, he served as president and chief executive officer from June

1996 through April 2004, when he helped transform TI from a broad-based conglomerate to a semiconductor company focused on making chips for the signal-processing markets that fed the wireless and Internet revolutions. His strategic focus and ability to quickly organize the elements needed to reconfigure the company laid the foundation for the TI of today – a semiconductor leader in signal-processing technology that has gained widespread recognition among customers, the financial community and the general public.

Tom joined TI in 1976, the same year he earned a master’s degree in electrical engineering from Purdue University. He started as an integrated circuit design engineer, spending his operational career in the company’s semiconductor business, holding management responsibilities in the Analog Products and Application-Specific Products businesses. In 1993, he was elected TI's executive vice president and president of the Semiconductor Group, where he turned in record profitability and growth. He remained in this position until his promotion to president and CEO of the company in June 1996. Tom is a member of the Catalyst board of directors, a nonprofit research and advisory organization working to advance women in business. He serves as a trustee of Southern Methodist University and a member of the Purdue University Engineering Visiting Committee. He is a member of the board of directors of J.C. Penney Company, Inc., and serves as a trustee on the Southwest Medical Foundation, the U.S. Japan Business Council and the National Center for Educational Accountability. He is a member of the National Academy of Engineering and the Institute of Electrical and Electronics Engineers. In addition to his master’s degree, Tom earned a bachelor’s degree in electrical engineering from Purdue, and received an honorary doctorate in engineering from Purdue in 1997.

The rules

2012-2013 Texas Instruments Analog Design Contest official rules
No purchase or payment necessary to enter or win.

For purposes of these rules, “TI” shall mean Texas Instruments Incorporated and its subsidiaries. TI is also referred to herein as “sponsor.”

Contest description

1. This Analog Design Contest (this “contest”) is designed to encourage engineering students to submit senior design projects that utilize TI technology (each, an “entry”). Prizes will be awarded to entrants who submit the best entries as determined by the judges in accordance with these rules.

Eligibility

1. This contest is open to design teams having a minimum of two team members or to single students working on senior design projects who have received permission from their professor and the contest coordinator. To be eligible to compete, each design team member (“entrant”) agrees to read and abide by the contest rules. A completed entry form must be submitted by each design team. The entry form must clearly identify each entrant.
2. This contest is offered to eligible entrants.
3. To be eligible, entrants must be 18 years of age or older and be a registered, undergraduate engineering student at an accredited engineering school in the United States or Canada (excluding schools located in the province of Quebec).
4. Each entrant may participate on only one design team.
5. Employees and agents of the sponsor and such individual’s immediate family (including spouse, parents, siblings, grandparents, grandchildren, step-children, step-parents and in-laws) and member of the same household are prohibited from entering this contest.

Entry requirements/judging

1. Entries must be in English.
2. Each design team may only submit one entry.
3. The contest begins November 30, 2012, at 12:01 a.m. Central time. Check the contest webpage for deadlines.
4. No submissions submitted after the dates specified will be considered. The sponsor reserves the right to cancel this contest before the end date at its sole discretion, and decline to award prizes if there are no eligible entrants.
5. All design idea entries must be implemented using three **different** TI devices: either three analog integrated circuits (“ICs”) or two analog

ICs and a TI processor (the “IC Requirements”). Analog ICs must come from the following categories: (i) data converters; (ii) amplifiers; (iii) power-management devices; (iv) interface devices; (v) MSP430™ (MCU+ADC); (vi) switches; (vii) RF devices; (viii) temperature sensors; (ix) clocks and timers; and (x) comparators. If you choose to use a TI processor, you may choose from the following: (i) MSP430 MCUs; (ii) DSPs; (iii) ARM devices; or (iv) OMAP™ processors. Other TI devices may be incorporated into the design, but only those integrated circuits in the categories above will be counted toward the IC requirements. Any design entries that do not comply with the IC requirements will be ineligible.

6. All design entries must be submitted to the sponsor by completing and submitting:

    1. The online entry form.
    2. A detailed written description of the design.
    3. A detailed explanation of each TI analog IC or TI processor used in the design and a specific description of how each analog IC or processor benefited the overall design.
    4. A video or photographs of the partially or fully built-out design.

7. Submissions shall be made through the following website: www.ti.com/analogdesigncontest. Entries must be submitted by the deadline to be considered. Entrants will be allowed to change or supplement their submissions up until the contest deadline.
8. The sponsor reserves the right, in its sole discretion, to disqualify anyone found to have tampered with the contest.
9. All entrants agree to follow and abide by the design idea requirements and judging criteria.
10. There is no entry fee. No purchase is required.
11. Upon request, TI will provide certain materials to the entrants necessary to meet the minimum design requirements needed to participate in this contest. Information regarding the process related to obtaining these materials will be provided by TI after entrants submit the online entry form. TI will not reimburse entrants for any out-of-pocket costs incurred or for efforts expended in connection with their

participation in the contest. Such costs are the responsibility of the entrants.

12. Decisions by the contest judges are final. The sponsor reserves the right to refrain from awarding any prize if there are no or minimal qualified entries.
13. A panel of judges, at least one of which will be an independent judge not related to the entrants, any partner school or sponsor, will review each design and rate each entry on the following criteria: (i) originality of design; (ii) quality of design; (iii) creativity of design; (iv) level of engineering analysis; (v) written description of how each TI analog integrated circuit or TI processor benefited the overall design. A maximum of 10 points will be awarded for each of the five categories identified in this section. An additional two points will be awarded to teams with designs that use a TI processor. The total number of points possible is 52. Subject to verification of eligibility and compliance with all contest rules, the design with the highest total design score shall be awarded the prizes in accordance with Section 21.
14. Judges for the contest will be fully competent and are required to be fair and impartial. Names of the contest judges will be provided upon request.

Prizes/Engibous Prize

1. **Prizes**: Any prizes will be awarded to the team members jointly and severally. The prize will be divided equally among the members of the winning design team, with the sponsor providing a winner's check in the applicable amount to each member of the winning team. In the case of online submissions, if there is a dispute regarding the identity of the entrant, the sponsor reserves the right to deem the account holder of the e-mail address as the entrant. Subject to these contest rules, the following prizes will be awarded to be split equally among the members:

1. First place: US$10,000.
2. Second place: US$7,500.
3. Third place: US$5,000.

1. Winners will be notified by the sponsor by the end of July. The prize will be awarded by the end of September. A list of winners will be posted on www.ti.com/analogdesigncontest.
2. If any member of the winning design team cannot be reached within 10 days of notification, or if a prize is returned with no forwarding address, the sponsor reserves the right to deem that team member's portion of the prize as forfeited.
3. United States and/or Canadian federal, state and local and any foreign taxes and other obligations are solely the responsibility of the winners. Prizes may be subject to reporting for tax and other purposes. Winners agree to supply the sponsor with any information necessary for tax reporting purposes and to cooperate in fulfilling all applicable legal requirements.
4. The members of any design team whose design idea is chosen for consideration for any award, as a condition of the award, may be required to submit further information concerning each team member's employment and residence. Also, as a condition of the award, the entrant(s) may be required to sign (i) other documents necessary to ensure nonexclusive license right to TI for such design ideas, and (ii) a liability/publicity release.

Intellectual property rights/licenses/publicity rights

1. **Entrants do not receive by way of or under the contest any intellectual property rights in any copyrights, patents, trademarks, trade names, technology, trade secrets or know-how of the sponsor or any third party.**
2. No entries will be returned to entrants, regardless of whether they are accepted. All entries and design submissions become the property of the sponsor.
3. All entrants warrant and represent that all design ideas and applications submitted are entirely original and that entrant is the owner of all interests in and rights to such designs. By submitting an entry to this contest, all entrants represent that there is no third party of any kind, whether an academic institution, commercial company, individual or governmental legal entity that has any proprietary or other interest in, claims or rights to, any intellectual property rights,

including trade secrets, “know-how,” copyright, patent, trademark or trade name, in any design ideas submitted under the contest. This representation is a requirement of participation in the contest.

4. All entrants agree, represent and guarantee that there are no obligations of any nature, legal or otherwise, that would prohibit, restrict or interfere with their participation in the contest or submission of their contest design idea. All entrants agree to obtain any necessary clearances, authorizations and/or approvals from any necessary third-party participation in all contest activities and any such approvals that are required as a condition of participation.
5. No confidential relationship is established between the sponsor and the entrant as a result of entering this contest. All entrants agree, represent and guarantee that their entries do not contain any confidential or proprietary information belonging to any third parties. None of the information submitted by the entrants will be treated by the sponsor as trade secrets, confidential information or as protected data under any obligation.
6. All entrants agree to be bound by the contest requirements for licensing of nonexclusive rights. Ownership of the design ideas (hereafter “designs”) shall remain with the entrants. Entrant hereby grants TI a nonexclusive, worldwide, perpetual, irrevocable and royalty-free license to use the designs in, or as part of, TI products, to implement the designs using TI products, to modify the designs for such uses, and to publish the designs for such uses by TI or by customers of TI under all applicable intellectual property rights related to the designs, including but not limited to patents, trade secrets, copyrights (including all moral and statutory copyrights), and trademarks. To the extent additional documents or actions are required under local law for an effective license to these rights, titles and interests for commercial purposes, entrants agree to fully cooperate in executing such further documents and in taking such further actions as are necessary. In such cases, entrants agree that commercialization license rights shall become effective upon completion of further required actions.
7. The nonexclusive license to TI of intellectual property rights, as described herein, is free of charge and without remuneration of any kind. All entrants agree that the opportunity to compete for prizes,

receive publicity, and increase one's understanding of TI products represents full and adequate consideration for license of these rights by all entrants. Prizes do not represent fixed-sum monetary remuneration of the licensing of intellectual property and rights in design submissions.

8. All entrants grant the sponsor the right to publicize their names, likeness, any information provided on the entry form, or their design idea entry in whatever manner without reservation or compensation. In certain countries, due to local requirements, it may be necessary for entrants to execute, in addition to this entry form, certain other documents for license of intellectual property rights, prior to any publication of the full design idea submission. In those countries, TI will make appropriate arrangements. Entries and design submissions may be published in sponsor or third-party publications.
9. Sponsor reserves the right to use information regarding entrants for future mailings subject to applicable laws and regulations and privacy policies. Texas Instruments' privacy policy can be found at http://www.ti.com/home_f_privacy.

General

1. **The contest shall be considered void where, and to the extent, prohibited by law.**
2. **The contest and its rules and conditions shall be governed by the laws of the state of Texas and any dispute arising out of this contest shall be brought in, and you hereby consent to exclusive jurisdiction and venue in, the Federal District Courts sitting in Dallas County, Texas.**
3. If any aspect of the contest or any rule or condition is found by a court of competent jurisdiction to be invalid, illegal or void, entrants agree to allow the sponsor to change such provision and, upon notice, to make it valid. Also, in such case, the remaining contest provisions shall remain in full force and effect and the contest shall proceed accordingly.
4. By entering this contest, each entrant agrees to release and hold the sponsor harmless from and against any losses, damages, rights, claims and actions of any kind arising from (i) an exclusion or disqualification

of an entrant pursuant to these rules; (ii) late, lost, misdirected or unsuccessful efforts to notify winners of any prize; (iii) forfeiture of a prize and the selection of an alternate winner; (iv) late, lost, delayed, damaged, misdirected, incomplete, illegible or unintelligible entries; (v) telephone, electronic, hardware or software program, network, Internet or computer malfunctions, failures or difficulties of any kind; (vi) failed, incomplete, garbled or delayed computer transmissions; (vii) any condition caused by events beyond the sponsor's control that may cause the contest to be disrupted or corrupted; and (viii) any injuries, losses or damages of any kind relating to a contest prize or acceptance, possession or use of the prize, or from participation in this contest.

5. The sponsor reserves the right to cancel, terminate, modify or suspend this contest if it becomes technically corrupted or if for any reason the Internet portion of the contest is not capable of running as planned, including infections by computer virus, bugs, tampering, unauthorized intervention, fraud, technical failures or any other causes beyond the control of the sponsor that corrupt or affect the administration, security, fairness, integrity or proper conduct of this contest.
6. **Any attempt to deliberately damage any website or undermine the legitimate operation of the contest is a violation of criminal and civil laws and should such an attempt be made, the sponsor reserves the right to seek damages or other remedies from any such persons responsible for the attempt to the fullest extent permitted by law.**